[redacted]

Copy [redacted]

RM E9F22

[redacted]

RESEARCH MEMORANDUM

FREE-FLIGHT PERFORMANCE OF 16-INCH-DIAMETER SUPERSONIC RAM-JET UNITS

I - FOUR UNITS DESIGNED FOR COMBUSTION-CHAMBER-INLET MACH NUMBER OF 0.12 AT FREE-STREAM MACH NUMBER OF 1.6 (UNITS A-2, A-3, A-4, AND A-5)

By William W. Carlton and Wesley E. Messing

Lewis Flight Propulsion Laboratory
Cleveland, Ohio

NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

WASHINGTON
September 22, 1949

[redacted]

319. 98/13

NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

RESEARCH MEMORANDUM

FREE-FLIGHT PERFORMANCE OF 16-INCH-DIAMETER SUPERSONIC RAM-JET UNITS

I - FOUR UNITS DESIGNED FOR COMBUSTION-CHAMBER-INLET MACH NUMBER OF 0.12 AT FREE-STREAM MACH NUMBER OF 1.6 (UNITS A-2, A-3, A-4, AND A-5)

By William W. Carlton and Wesley E. Messing

SUMMARY

Free-flight investigations have been conducted on four 16-inch-diameter ram-jet units to determine the performance at high subsonic and supersonic velocities. The units were released from an airplane at high altitudes. The engine thrust and the force of gravity accelerated the ram-jet units to high subsonic and supersonic Mach numbers. Data for evaluating the performance were obtained from radio-telemetering and radar-tracking equipment.

The effects of free-stream Mach number and gas total-temperature ratio on diffuser total-pressure recovery, thrust coefficient, and external drag coefficient are correlated. Also included are the performance data of the individual ram-jet units for a range of free-stream Mach numbers from 0.38 to 1.73 and for gas total-temperature ratios between 1.0 and 6.6.

A maximum combustion efficiency of 91 percent occurred in one unit at a free-stream Mach number of 1.70, with a diffuser total-pressure recovery of 0.90. The corresponding gas total-temperature ratio of 5.1 was equivalent to an exhaust-gas total temperature of 4050° R. A net acceleration (excluding gravity) of 2.0 g's and a net thrust coefficient of 0.56 were produced.

INTRODUCTION

As part of an extensive study of the performance of ram jets, the NACA Lewis laboratory is conducting a free-flight investigation of 16-inch-diameter ram-jet units. The units are released from an airplane at high altitudes and accelerated to supersonic velocities by the engine thrust and the force of gravity.

The purpose of the investigation is to provide performance data on full-scale units operating under actual atmospheric conditions at high subsonic and supersonic Mach numbers. In addition to subsonic and supersonic data obtainable from wind-tunnel research, the flight investigation provides data throughout the transonic range. Data are also being obtained under conditions of rapid acceleration with accompanying changes in inlet conditions due to large variations in altitude and Mach number.

The investigation is being conducted off the Virginia coast near the NACA Langley laboratory. Four ram-jet designs (designated 16-A, 16-B, 16-C, and 16-D) of different inlet and outlet diameters are used in order to obtain data over a range of combustion-chamber velocities. Data are obtained at different values of fuel-air ratio by presetting the fuel regulator. Continuous data records are obtained by radio-telemetering and radar-tracking equipment during the flight.

Data obtained from the first ram-jet unit investigated (designated 16-A-1) are discussed in reference 1. Data obtained with the succeeding four A-type ram-jet units are presented herein. Time histories of the performance are presented for altitudes between 36,000 feet and sea level and free-stream Mach numbers from 0.38 to 1.73. Also included are the effects of free-stream Mach number and gas total-temperature ratio on diffuser total-pressure recovery, thrust coefficient, and external drag coefficient.

Insufficient data are available from the four ram-jet units discussed herein to permit correlation of the variables affecting combustion efficiency. Time histories of these variables are therefore presented, showing only simultaneous values.

APPARATUS

The ram-jet unit consisted of an outer shell with four stabilizing fins at the rear and a centrally located body in the diffuser section that housed the telemetering equipment and the fuel system. The gross weight of each unit was approximately 525 pounds. A ram-jet unit suspended from an airplane is shown in figure 1. A cutaway view of a typical ram jet is shown in figure 2.

The four ram-jet units investigated were designated 16-A-2, 16-A-3, 16-A-4, and 16-A-5. (The 16-A refers to the maximum diameter and the model design and the numeral is the unit number.) Model A was designed for a combustion-chamber-inlet velocity of 165 feet per second (Mach number, 0.12) at a free-stream Mach number of 1.60 and a gas total-temperature ratio of 4.0. This heat addition is equivalent to operation at a fuel-air ratio of 0.067 and a combustion efficiency of 60 percent at sea-level altitude. The diffuser was a single oblique-shock type with no internal contraction. The spike cone angle was 50° and the diffuser was designed for a normal shock at the inlet lip at a free-stream Mach number of 1.60 and a combustion-chamber-inlet Mach number of 0.12. The lip of the outer shell was positioned to intercept the oblique shock at a free-stream Mach number of 1.80. A schematic cross-sectional diagram of a ram-jet unit, including the dimensions for model A, is presented in figure 3.

The fuel system (fig. 4) included a fuel tank, a fuel regulator, and a fuel-spray ring. Helical tubing was coiled inside the fuel tank to store helium at a pressure of 3200 pounds per square inch. Fuel was stored in a flexible synthetic-rubber fuel cell that has a capacity of $8\frac{1}{2}$ gallons. The fuel used was 73-octane gasoline (AN-F-23a). Free-stream total pressure actuated the fuel regulator and controlled the pressure of helium on the fuel cell. This helium pressure forced the fuel into three fuel lines, each of which contained a spring-loaded reducing valve and a separate set of spray nozzles. Only one set of these nozzles operated at the start of each flight, which permitted the use of high fuel pressures at low fuel-flow rates. As the free-stream total pressure increased, the regulator increased the pressure in the fuel tank and thus provided greater rates of fuel flow. Increased fuel pressure successively opened the second and third reducing valves, which brought more nozzles into operation at the desired values of free-stream total pressure. The regulator could be adjusted to alter the fuel pressure and different reducing valve springs could be used to change the opening pressure of each set of nozzles.

A ducted-airfoil-type flame holder with intermediate gutters (fig. 5) was used in units A-2, A-3, and A-4. Two electrically ignited magnesium flares mounted upstream of the flame holder initiated the combustion process. This type of flame holder was previously investigated in a test stand at low combustion-chamber-inlet velocities and at pressures corresponding to nearly sea-level altitude. Ram-jet unit A-5 employed a rake-type flame holder with seven magnesium flares (fig. 6). A similar flame holder was investigated in a wind tunnel (reference 2) over approximately the same range of combustion-chamber-inlet conditions encountered in the flight investigation of ram-jet unit A-5.

INSTRUMENTATION 1152

A portable radar-tracking unit, type SCR-584, with both optical and autotracking facilities was used to obtain a time history of the position of the ram-jet unit relative to the ground during flight. The telemetering-receiver antenna was directionally controlled by the radar tracker in order to maintain the strongest possible telemetering signal. A plotter was synchronized with the radar tracker and automatically charted the course of the ram-jet units.

The eight-channel telemetering equipment in the ram-jet unit transmitted the following data to two ground receiving recorders:

1. Axial net acceleration

2. Pressure drop across fuel-flow orifice

3. Free-stream total pressure

4. Free-stream static pressure

5. Static pressure in diffuser, $4\frac{5}{8}$ inches downstream of diffuser inlet, station 2 (fig. 3)

6. Dynamic pressure in diffuser, 65 inches downstream of diffuser inlet, station 3 (fig. 3)

7. Total pressure at diffuser outlet, station 4 (fig. 3)

8. Static pressure at engine outlet, exhaust-nozzle outlet, station 7 (fig. 3)

The axial net acceleration (total acceleration minus the component due to gravity) was measured by a cantilever-beam-type accelerometer, with the beam fixed at one end, weighted at the other, and free to move in the direction of the axis of the ram jet. The force of gravity did not affect the deflection of the beam because it acted equally upon both the ram jet and the accelerometer. The fuel-flow orifice was calibrated to determine the

rates of fuel flow directly from the measured pressure drop. The telemetering antenna of the ram-jet unit was also a pitot-static tube from which the free-stream total and static pressures were obtained. A single flush wall orifice measured the static pres-
1152 sure in the diffuser inlet at station 2. This pressure was used to determine the transitions between subsonic and supersonic flow at station 2 when a shock passed over the orifice. Dynamic pressure in the diffuser at station 3 was the measured difference in pressure between two manifolds, one connected to eight total-pressure tubes and the other connected to two static-pressure tubes. The air flow was calculated at this station. The total pressure at the diffuser outlet was measured farther downstream (station 4) by eight total-pressure tubes manifolded together. A single flush wall orifice was placed just inside the exhaust-nozzle outlet to determine the outlet static pressure used for temperature and thrust calculations.

PROCEDURE

Theoretical calculations were made to determine the probable performance of the ram-jet units. The flight path of the ram-jet unit was calculated for combustion at a fuel-air ratio of 0.067 and a combustion efficiency of 60 percent. It was determined that the ram jet would reach its design conditions shortly before impact if it adhered to the calculated flight path. Air flow was calculated throughout the flight. The rates of fuel flow necessary to maintain a fuel-air ratio of 0.067 were then determined and plotted as a function of free-stream total pressure. Before each flight the fuel regulator, which was actuated by the free-stream total pressure, and the spring tensions in the fuel valves were adjusted to maintain the desired fuel-air ratio. Deviations from the scheduled free-stream Mach number had little effect on the required fuel flow because the regulator was actuated by the free-stream total pressure, which in turn largely determined the air flow. Deviation from the assumed combustion efficiency, however, would affect the air flow and alter the fuel-air ratio. The altitude for releasing each ram-jet unit was determined by the predicted fuel consumption in order to exhaust the fuel before impact and obtain drag data without combustion at high flight Mach numbers.

Immediately after each drop, an atmospheric survey was made by the descending airplane to determine static temperature and pressure as a function of true altitude. True altitude was determined by radar-tracking the airplane. Weather balloons were released and radar-tracked to determine the wind-velocity corrections for the different altitudes.

GENERAL METHOD OF CALCULATION

Free-Stream Conditions

Free-stream static temperatures and pressures encountered by the ram-jet unit during a flight were calculated from atmospheric-survey and radar-tracking data. These pressures were used in the performance calculations in preference to the telemetered static pressures, which included possible shock-wave and interference effects from the ram-jet unit. The free-stream velocity of the ram-jet unit was determined by plotting both the radar velocity, obtained by differentiating the flight path, and the velocity obtained by integrating the total acceleration of the ram jet. An average velocity curve was faired and corrected for the variation in wind velocity encountered at different altitudes in order to obtain the relative air velocity. From the relative air velocity and the free-stream static temperature and pressure, it was possible to calculate the remaining free-stream conditions of free-stream Mach number, total temperature, and total pressure. Calculated values of total pressure were believed to be less subject to possible error than the measured telemetered values and were therefore used in the performance calculations wherever possible. 1152

Performance Calculations

Air flow through the unit was calculated from the data obtained at station 3, where the dynamic pressure in the diffuser was measured. In order to calculate the air flow, the total pressure was assumed equal to the measured total pressure at the diffuser outlet and the total temperature was assumed equal to the free-stream total temperature. The flow conditions at the diffuser outlet were then calculated by assuming isentropic compression, in accordance with the area change, between station 3 and the diffuser outlet. Fuel flow was determined from the telemetered static-pressure drop across a calibrated orifice in the fuel line. Calculation of the fuel-air ratio completed the flow calculations at the combustion-chamber inlet.

On the basis of wind-tunnel investigations of similar flame holders, the total-pressure drop across the flame holder was assumed to be twice the dynamic pressure at the upstream side of the flame holder. For this total-pressure loss, the flow conditions at the downstream side of the flame holder were calculated assuming no change in total temperature from the free-stream value.

The flow conditions after the combustion process were determined by two independent methods. When no choking existed at the engine outlet, the calculations were based on a trial-and-error solution involving the relations for heat addition in a constant-area pipe. For the choking condition, the calculations involved the continuity expression for mass flow. The heat-addition expression could also be used for the choking condition. The good agreement obtained by both methods tended to justify the necessary assumptions made for the constant-area heat-addition expression. When choking occurred in the exhaust nozzle, the static pressure at the outlet was obtained from the telemetered data. The total temperature at the outlet necessary for this condition was then calculated by using the continuity expression for mass flow. When subsonic velocity existed in the exhaust nozzle, a trial-and-error solution was required. In this case, it was assumed that all the heat was released in the constant-area section of the combustion chamber and that no friction losses occurred in the combustion chamber and the exhaust nozzle. The trial-and-error solution involved tentative selection of a total temperature after combustion at station 6, calculation of total pressure and Mach number after combustion, and calculation of flow conditions at the engine outlet by isentropic expansion for the area change. If the static pressure at the outlet did not equal the measured static pressure, the calculations were repeated for different values of total temperature after combustion. In some cases, the telemetered static pressure at the engine outlet was unreliable due to vibratory burning. The free-stream static pressure was used as a substitute value under these conditions. Both methods of calculation involved the assumption that all the fuel was vaporized in the ram jet. Included in the calculations were the variations in specific-heat ratio of the gases with combustion.

Net thrust was calculated as the difference in the momentum of the exhaust gases at the engine outlet and the momentum of the free-stream air. External drag was determined as the difference between the net thrust and the product of the net acceleration times the weight of the ram-jet unit. Thrust and external-drag coefficients were calculated for the maximum cross-sectional area.

Combustion efficiency was determined as the increase in enthalpy of the fuel-air mixture across the combustion chamber divided by the available chemical energy of the fuel and the flares. The gas total-temperature ratio was obtained by dividing the calculated total temperature of the exhaust gases at the engine outlet by the total temperature of the air at the combustion-chamber inlet.

The equations used in determining the free-stream conditions and the performance are given in the appendix.

RESULTS AND DISCUSSION

Time histories of the ram-jet-unit performance are presented in figures 7 to 10. In general, these figures include resultant flight conditions, independent test variables, diffuser conditions, combustion-chamber-inlet variables, and performance variables. The solid curves are measured values and the broken lines represent approximated values. Such approximations were made wherever the telemetering records were so vibratory that no exact data could be measured, although the trend in the data could be clearly established.

Unit A-2 was released at a free-stream Mach number of 0.38 and an altitude of 30,000 feet, as compared with initial free-stream Mach numbers of 0.55 to 0.59 and altitudes of 32,000 to 36,000 feet for the other units. The variation in launching conditions, however, is believed to have had little effect on the final performance of the ram-jet units.

Combustion Performance

In the comparison of the combustion performance of the four ram-jet units, it should be recalled that the units were similar in construction except for the flame holders.

The effects of fuel flow and flame-holder design on the free-stream Mach numbers are shown in figure 11. For comparative purposes, fuel flow is shown as a function of free-stream total pressure because this pressure actuated the fuel regulator. The calculated fuel flow necessary to obtain a fuel-air mixture of 0.067 is included. No fuel flow data were obtained for unit A-2.

Combustion occurred in unit A-2 only momentarily. As a result, the maximum free-stream Mach number was only 0.92 shortly before impact. Units A-3 and A-4 had relatively high fuel flows and reached maximum free-stream Mach numbers of 1.34 and 1.25, respectively. Combustion was sporadic throughout the flights with regions of extreme vibration and very low combustion efficiency. Unit A-5 operated at low rates of fuel flow and continuously good combustion with rapidly increasing flight Mach numbers occurred throughout most of the flight. A maximum free-stream Mach number of 1.73 occurred at an altitude of 4900 feet. No data were obtained below this altitude. The improvement in combustion in unit A-5 may be attributed to both the change in flame-holder design and the lower values of fuel flow.

In general, the data indicate that rich fuel-air ratios were detrimental to good combustion. Except for unit A-2, the lowest combustion efficiency was obtained in unit A-4 where the fuel-air ratio (fig. 9(d)) was in excess of 0.084. The combustion efficiency never exceeded 37 percent (fig. 9(e)). Telemeter records showed regions of pulsating, intermittant burning throughout the flight. As a result, some data were not obtainable in unit A-4 between $33\frac{1}{2}$ and 49 seconds (figs. 9(c) to 9(e)). Unit A-3 also encountered low combustion efficiencies at fuel-air ratios of 0.084 to 0.088 (figs. 8(d) and 8(e)).

The effect of lean fuel-air ratios on combustion was indicated only by the data for unit A-5. A low combustion efficiency of 40 percent occurred at a fuel-air ratio of 0.043 (figs. 10(d) and 10(e)). As the fuel-air ratio suddenly increased to 0.065, the combustion efficiency increased to 52 percent. In general, for the flight conditions encountered with unit A-5, combustion efficiencies exceeded approximately 40 percent when the ram jet was operating within a fuel-air-ratio range of 0.043 to 0.070.

An increase in combustion efficiency occurred with an increase in combustion-chamber-inlet static pressure and temperature. For example, the combustion efficiency in unit A-5 (fig. 10(e)) increased from 52 percent at 31 seconds to 91 percent at 38 seconds with increases in combustion-chamber-inlet static pressure from 2800 to 7200 pounds per square foot and static temperature increases from 635° to 790° R (fig. 10(d)). This increase in combustion efficiency occurred at approximately constant values of fuel-air ratio (0.062 to 0.065) and combustion-chamber-inlet velocity (150 to 160 ft/sec). During this time interval, however, it was noted that the third set of fuel nozzles became operative and increased the number of nozzles discharging fuel (fig. 10(b)). The resultant change in fuel pattern and degree of fuel atomization may have had some beneficial effect and may partly account for the large increase in combustion efficiency.

The effect of flame-holder design on the combustion process could be determined only at a fuel-air ratio of 0.067 and low values of combustion-chamber-inlet static pressure of 1000 pounds per square foot and static temperature of 485° R. Under these conditions with the ducted-type flame holder, a combustion efficiency of 20 percent was obtained at 22 seconds (fig. 8(e)) as compared with a combustion efficiency of 46 percent obtained at 16.5 seconds with the rake-type flame holder (fig. 10(e)).

The performance of unit A-5 (fig. 10) indicated that a high combustion efficiency of 91 percent could be obtained at a free-stream Mach number of 1.70, which sustained a diffuser total-pressure recovery of approximately 0.90. A maximum net acceleration of 2.0 g's and a thrust coefficient of 0.56 were produced. A gas total-temperature ratio of 5.1 existed, which was equivalent to an exhaust-gas total temperature of 4050° R.

Diffuser Total-Pressure Recovery

The total-pressure recovery across the diffuser is shown in figure 12 as a function of free-stream Mach number for all four ram-jet units. Lines of constant gas total-temperature ratio were faired according to the collective data points.

At a constant value of free-stream Mach number, a decrease in gas total-temperature ratio was accompanied by a decrease in total-pressure recovery largely due to increasing shock losses within the diffuser. For example, at a free-stream Mach number of 1.20, the diffuser total-pressure recovery decreased from 0.94 to 0.52 with a decrease in gas total-temperature ratio from 5.0 to 1.0. The decrease in gas total-temperature ratio resulted in diffuser-outlet conditions of higher velocity, lower static pressure, and a reduction in total pressure necessary to maintain mass continuity. When supersonic velocity existed within the diffuser, this reduction in total pressure was made possible only by the presence of a normal shock with its accompanying total-pressure loss. The minimum value of free-stream Mach number at which shock occurred within the diffuser was approximately 0.60 at a gas total-temperature ratio of 1.2 (fig. 7) at 16 seconds after release with the transition from subsonic to supersonic flow at station 2 ($4\frac{5}{8}$ in. downstream of the diffuser inlet).

Thrust Coefficient

The effects of free-stream Mach number and gas total-temperature ratio on the net-thrust coefficients are shown in figure 13. As defined in the appendix, the net thrust is the total change in momentum of the air and the fuel flowing through the ram jet. At constant gas total-temperature ratios, the thrust coefficient increased with increasing free-stream Mach numbers until the total-pressure recovery declined rapidly because of shock in the diffuser.

At sonic free-stream velocity, a gas total-temperature ratio of at least 2.0 was necessary for a positive thrust coefficient. At this velocity, the thrust coefficient varied from -0.20 to 0.48 with variations in the gas total-temperature ratio from 1.0 to 6.0.

1152

External Drag Coefficient

The effect of free-stream Mach number and gas total-temperature ratio on the external drag coefficient is shown in figure 14. The external drag equals the total change of momentum of the air flowing outside the ram jet and therefore includes the additive drag at the diffuser inlet as well as the total external drag on the shell and the fins. The term additive drag is more fully discussed in reference 3. The dashed curve represents the minimum external drag coefficients encountered at various free-stream Mach numbers. These minimum values occurred at conditions of minimum additive drag and maximum engine air flow when the external-flow conditions ahead of the diffuser inlet were unaffected by variations in heat addition. Increasing the heat addition above a certain value will reduce the air flow; consequently, the divergence of the streamlines ahead of the inlet becomes greater. Increased pressures acting on these diverging streamlines give rise to increased additive drag. The increased pressures also increase the wave drag on the shell exterior. The effect of an increase in heat addition on the external drag coefficient was most noticeable at supersonic Mach numbers. For example, at a free-stream Mach number of 1.70, increasing the gas total-temperature ratio from 4.0 to 5.0 increased the external drag coefficient from 0.17 to 0.32.

The lowest value of external drag coefficient (approximately 0.115) occurred at free-stream Mach numbers of 0.90 to 1.00. The maximum external drag coefficients for any given gas total-temperature ratio occurred at free-stream Mach numbers between 1.10 and 1.20. When the ram jet was operating at the design condition (gas total-temperature ratio of 4.0 and free-stream Mach number of 1.60), the external drag coefficient was 0.169, which was the minimum value for the free-stream Mach number of 1.60.

SUMMARY OF RESULTS

From the data obtained from free-flight investigations of four 16-inch-diameter supersonic ram-jet units with a range of free-stream Mach numbers of 0.38 to 1.73 and gas total-temperature ratios between 1.0 and 6.6, the following results were observed:

1. A maximum combustion efficiency of 91 percent was obtained in unit A-5 at a free-stream Mach number of 1.70, which sustained a diffuser total-pressure recovery of 0.90. The gas total-temperature ratio of 5.1 was equivalent to an exhaust-gas total temperature of 4050° R. A maximum net acceleration of 2.0 g's and a thrust coefficient of 0.56 were produced.

1152

2. For the flight conditions encountered, combustion efficiencies from 40 to 91 percent were obtained with unit A-5 during operation within a fuel-air-ratio range of 0.043 to 0.070. At the leanest fuel-air ratio, 0.043, a low combustion efficiency of about 40 percent occurred in unit A-5. As the fuel-air ratio suddenly increased to 0.065, the combustion efficiency increased to 52 percent. Fuel-air ratios above 0.084 produced sporadic combustion accompanied by extremely low combustion efficiency in units A-3 and A-4. For unit A-5, at constant values of fuel-air ratio (0.062 to 0.065) and combustion-chamber-inlet velocity (150 to 160 ft/sec), increases in combustion-chamber-inlet static pressure from 2800 to 7200 pounds per square foot and static temperature from 635° to 790° R increased the combustion efficiency from 52 to 91 percent.

3. As expected, a decrease in gas total-temperature ratio was accompanied by a decrease in diffuser total-pressure recovery largely due to increasing shock losses within the diffuser. At a free-stream Mach number of 1.20, the diffuser total-pressure recovery decreased from 0.94 to 0.52 with a decrease in gas total-temperature ratio from 5.0 to 1.0.

4. Thrust coefficients increased with an increase in gas total-temperature ratio and flight Mach numbers within the range of the data obtained. At a free-stream Mach number of 1.00, the thrust coefficient rose from -0.2 to 0.48 as the gas total-temperature ratio increased from 1.0 to 6.0.

5. For a given gas total-temperature ratio, the minimum value of external drag coefficient (approximately 0.115) occurred at free-stream Mach numbers of 0.90 to 1.00 and the maximum values occurred at free-stream Mach numbers of 1.10 to 1.20. At a free-stream Mach number of 1.70, increasing the gas total-temperature ratio from 4.0 to 5.0 increased the external drag coefficient from 0.17 to 0.32 as the flow conditions ahead of the inlet were altered.

Lewis Flight Propulsion Laboratory,
National Advisory Committee for Aeronautics,
Cleveland, Ohio.

1152

APPENDIX - METHODS OF CALCULATION

Symbols

The following symbols are used in this report:

A	cross-sectional area, sq ft
A_{cr}	critical area necessary to bring local Mach number isentropically to unity, sq ft
A_{max}	maximum cross-sectional area, sq ft
a_n	axial acceleration component due to difference between net thrust and drag, g's
C_D	external drag coefficient
C_F	net-thrust coefficient
D	external drag, lb
F_n	net thrust, lb
g	acceleration due to gravity, ft/sec^2
H_a	enthalpy of air and fuel before combustion, Btu/lb air
H_g	enthalpy of burned gases at exhaust-gas temperature, Btu/lb exhaust gas
h	lower heating value of fuel, 18,500 Btu/lb
M	Mach number
P	total pressure, lb/sq ft
p	static pressure, lb/sq ft
Q	rate of heat release of flares, Btu/sec
q	dynamic pressure, lb/sq ft
R	gas constant, ft-lb/($^{\circ}$R)(lb)
T	total temperature, $^{\circ}$R

t static temperature, $^{\circ}R$

V velocity, ft/sec

W gross weight of ram jet, lb 1152

W_a air flow, lb/sec

W_f fuel flow, lb/sec

W_i initial gross weight of ram jet, lb

γ ratio of specific heat at constant pressure to specific heat at constant volume

η_b combustion efficiency, percent

τ time, sec

Subscripts:

0 free stream

0,B free stream behind normal shock

1 diffuser inlet

2 $4\frac{5}{8}$ inches downstream of air inlet (at static orifice)

3 65 inches downstream of air inlet (at dynamic-pressure rake)

4 diffuser outlet or combustion-chamber inlet (upstream side of flame holder)

5 combustion-chamber inlet (downstream side of flame holder)

6 combustion-chamber outlet

7 exhaust-nozzle outlet

Calculations

An atmospheric survey is made after the drop of a ram-jet unit. From the survey, the free-stream static temperature t_0 and pressure p_0 are determined as a function of true altitude, as obtained by radar-tracking the descending airplane. From the radar data, the position of the ram-jet unit as a function of time after release is determined. By differentiation, the velocity and the trajectory angle of the unit are obtained. The velocity of the ram-jet unit is calculated by integrating the total acceleration, which is the sum of the telemetered net acceleration and the acceleration component due to gravity. An average velocity curve is drawn and corrected by applying wind-velocity corrections obtained from radar-tracking a weather balloon. The corrected relative air velocity is defined as the free-stream velocity V_0 of the ram jet.

Free-stream conditions are determined in accordance with the following general equations for compressible flow:

$$M = \frac{V}{\sqrt{\gamma g R t}} \tag{1}$$

$$T = t\left(1 + \frac{\gamma-1}{2}\right)M^2 \tag{2}$$

$$P = p\left(1 + \frac{\gamma-1}{2} M^2\right)^{\frac{\gamma}{\gamma-1}} \tag{3}$$

The free-stream total pressure measured by the telemetering equipment is actually the total pressure as measured behind a normal shock when $M_0 > 1.0$ and is designated $P_{0,B}$. In order to obtain P_0 from the telemetered $P_{0,B}$, it is corrected for the normal-shock loss in accordance with

$$P_0 = P_{0,B}\left[\frac{(\gamma-1)M_0^{\,2} + 2}{(\gamma+1)M_0^{\,2}}\right]^{\frac{\gamma}{\gamma-1}}\left(\frac{2\gamma}{\gamma+1} M_0^{\,2} - \frac{\gamma-1}{\gamma+1}\right)^{\frac{1}{\gamma-1}} \tag{4}$$

These telemetered values of P_0 are used only in the performance calculation when values cannot be calculated from the radar data.

The Mach number at station 2 is determined from the following general equation. The static pressure is measured at station 2 and the total pressure is assumed equal to the free-stream total pressure minus external shock losses.

$$M = \sqrt{\frac{2}{\gamma-1}\left[\left(\frac{P}{p}\right)^{\frac{\gamma-1}{\gamma}} - 1\right]} \tag{5}$$

The ram-jet air flow is determined from the data available at station 3 by assuming that the total pressure at station 3 equals the measured total pressure at station 4 and that the total temperature equals the free-stream total temperature. The method involves determining

$$p_3 = P_3 - (P_3 - p_3) \tag{6}$$

the Mach number at station 3 from equation (5), and

$$W_a = p_3 A_3 M_3 \left(\frac{P_3}{p_3}\right)^{\frac{\gamma-1}{2\gamma}} \sqrt{\frac{\gamma g}{RT_3}} \tag{7}$$

For the conditions at the diffuser outlet, the total pressure P_4 is known and Mach number M_4 is determined from M_3 by calculating $A_{cr,3}/A_3$ from the general equation

$$\frac{A_{cr}}{A} = M\left(\frac{\frac{\gamma+1}{2}}{1 + \frac{\gamma-1}{2}M^2}\right)^{\frac{\gamma+1}{2(\gamma-1)}} \tag{8}$$

and then, because $P_4 = P_3$ and $T_4 = T_3$

$$\frac{A_{cr,4}}{A_4} = \left(\frac{A_{cr,3}}{A_3}\right)\left(\frac{A_3}{A_4}\right) \tag{9}$$

From equation (8), M_4 can be determined for the value of $A_{cr,4}/A_4$. It is then possible to calculate p_4 from equation (3), t_4 from equation (2), and V_4 from equation (1).

The conditions before heat addition in the combustion chamber, station 5, are calculated for a total-pressure drop across the flame holder of twice the dynamic pressure in front of the flame holder. Thus

$$\frac{P_5}{P_4} = \frac{P_4-2q_4}{P_4} = 1 - \frac{2q_4}{P_4} \tag{10}$$

but

$$q_4 = P_4 \frac{\gamma}{2} M_4^{\,2} \left(1 + \frac{\gamma-1}{2} M_4^{\,2}\right)^{-\frac{\gamma}{\gamma-1}} \tag{11}$$

therefore

$$P_5 = P_4 - \frac{\gamma M_4^{\,2} P_4}{\left(1 + \frac{\gamma-1}{2} M_4^{\,2}\right)^{\frac{\gamma}{\gamma-1}}} \tag{12}$$

In order to determine M_5, it is necessary to determine

$$\frac{A_{cr,5}}{A_5} = \left(\frac{P_4}{P_5}\right)\left(\frac{A_{cr,4}}{A_4}\right) \tag{13}$$

The Mach number M_5 can then be determined from equation (8).

The method used to determine the conditions after heat addition (station 6) involves the trial-and-error process of equations (14) and (15), which are derived in reference 4.

$$\left(1 + \frac{W_f}{W_a}\right)^2 \frac{T_6}{T_5} = \left(\frac{M_6}{M_5}\right)^2 \left(\frac{\gamma_6}{\gamma_5}\right)\left(\frac{1 + \gamma_5 M_5^{\,2}}{1 + \gamma_6 M_6^{\,2}}\right)^2 \left(\frac{1 + \frac{\gamma_6-1}{2} M_6^{\,2}}{1 + \frac{\gamma_5-1}{2} M_5^{\,2}}\right) \tag{14}$$

$$\frac{P_6}{P_5} = \left(\frac{1 + \gamma_5 M_5{}^2}{1 + \gamma_6 M_6{}^2}\right) \frac{\left(1 + \frac{\gamma_6 - 1}{2} M_6{}^2\right)^{\frac{\gamma_6}{\gamma_6 - 1}}}{\left(1 + \frac{\gamma_5 - 1}{2} M_5{}^2\right)^{\frac{\gamma_5}{\gamma_5 - 1}}} \tag{15}$$

When M_7 is less than 1.0 (no choking at outlet), T_6 is assumed and the corresponding γ_6 is determined for the known fuel-air ratio. The quantity $\left(1 + \frac{W_f}{W_a}\right)^2 \frac{T_6}{T_5}$ is determined and M_6 and P_6 are determined from equations (14) and (15). The assumptions $P_6 = P_7$ and $T_6 = T_7$ are made.

$$\frac{A_{cr,7}}{A_7} = \left(\frac{A_{cr,6}}{A_6}\right)\left(\frac{A_6}{A_7}\right) \tag{16}$$

Mach number M_7 can thus be determined from equations (8) and (16). Total pressure P_6 is the product of equations (12) and (15) and is assumed equal to P_7. It is then possible to determine the value of p_7 from equation (3). This value should equal the measured value of p_7 from the telemeter records. If they do not agree, the procedure is repeated, assuming a different value for T_6. When M_7 is equal to unity (choking at engine outlet), the total temperature after combustion is found directly from the relation for mass continuity

$$T_7 = \frac{g\gamma_7(\gamma_7+1)A_7{}^2}{2R_7} \frac{p_7{}^2}{(W_a+W_f)^2} \tag{17}$$

Assumed values of γ_7 and R_7 are used and then checked to agree with T_7.

1152

Combustion efficiency is determined by the equation

$$\eta_b = \frac{\left(1 + \frac{W_f}{W_a}\right)H_g - H_a}{\frac{W_f}{W_a} h + \frac{Q}{W_a}} \tag{18}$$

The enthalpy values are obtained from reference 5.

Thrust coefficient is defined as

$$C_F = \frac{2F_n}{\gamma_0 p_0 M_0^2 A_{max}} \tag{19}$$

where

$$F_n = \left(\frac{W_a + W_f}{g}\right) V_7 - \left(\frac{W_a}{g}\right) V_0 + A_7(p_7 - p_0) \tag{20}$$

$$V_7 = M_7 \left(\frac{\gamma_7 g R_7 T_7}{1 + \frac{\gamma_7 - 1}{2} M_7^2}\right)^{\frac{1}{2}} \tag{21}$$

The weight of the ram jet at any time during the flight is

$$W = W_i - \int_0^\tau W_f \, d\tau \tag{22}$$

The external drag is determined as

$$D = F_n - Wa_n \tag{23}$$

The external drag coefficient is defined as

$$C_D = \frac{D}{\frac{\gamma_0}{2} p_0 M_0^2 A_{max}} \tag{24}$$

In order to facilitate the calculations, graphs were made of equations (12), (13), (14), and (15). Wherever possible, tables from reference 6 are used for equations (2), (3), (4), (5), and (8).

1152

REFERENCES

1. Kinghorn, George F., and Disher, John H.: Free-Flight Investigation of 16-Inch-Diameter Supersonic Ram-Jet Unit. NACA RM E8A26, 1948.

2. Wilcox, Fred A., and Howard, Ephraim M.: Comparison of Two Fuels in Bumblebee 18-Inch Ram Jet Incorporating Rake-Type Flame Holder. NACA RM E8F11, 1948.

3. Ferri, Antonio, and Nucci, Louis M.: Preliminary Investigation of a New Type of Supersonic Inlet. NACA RM L6J31, 1946.

4. Perchonok, Eugene, Sterbentz, William H., and Moore, Stanley H.: Indirect Methods for Obtaining Ram-Jet Exhaust-Gas Temperature Applied to Fuel-Metering Control. NACA RM E7H27, 1948.

5. Turner, L. Richard, and Lord, Albert M.: Thermodynamic Charts for the Computation of Combustion and Mixture Temperatures at Constant Pressure. NACA TN 1086, 1946.

6. The Staff of the Ames 1- by 3-Foot Supersonic Wind Tunnel Section: Notes and Tables for Use in the Analysis of Supersonic Flow. NACA TN 1428, 1947.

1152

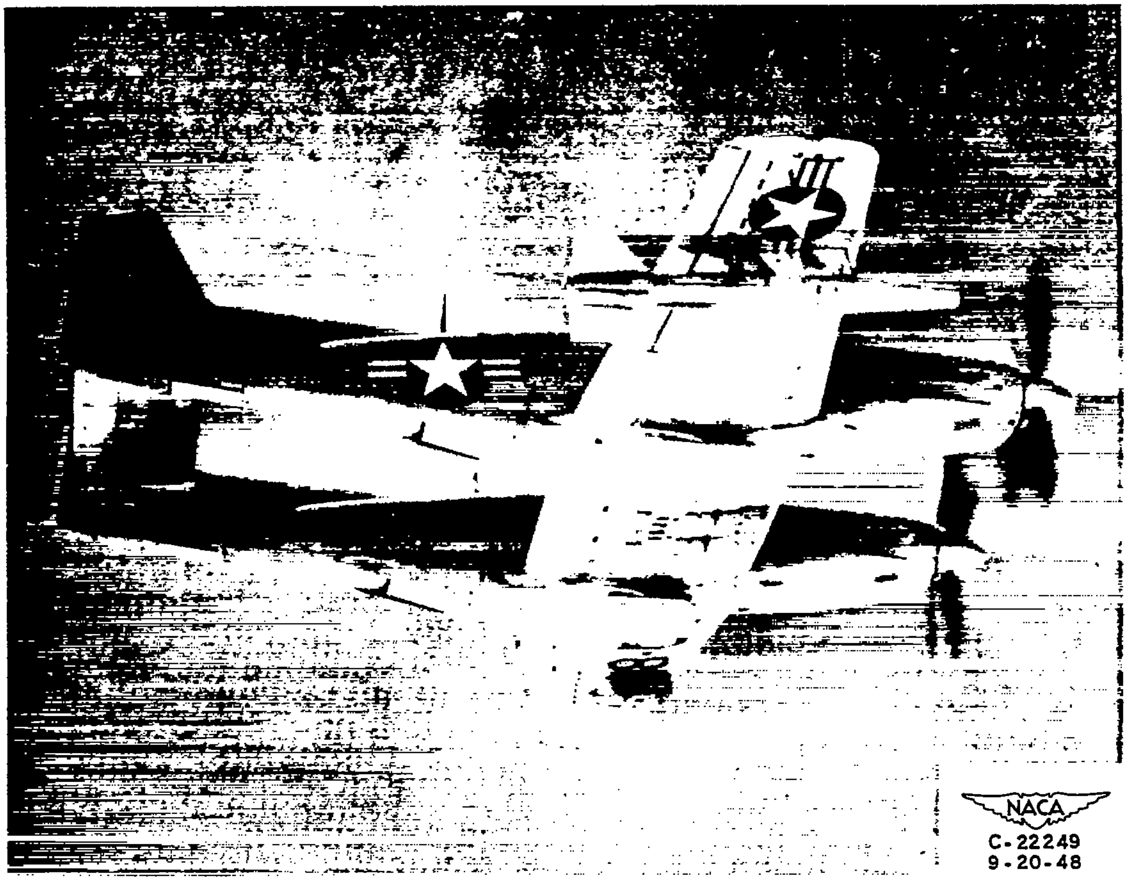


Figure 1. - Supersonic 16-inch ram-jet unit mounted beneath airplane wing.

[redacted]

[redacted]

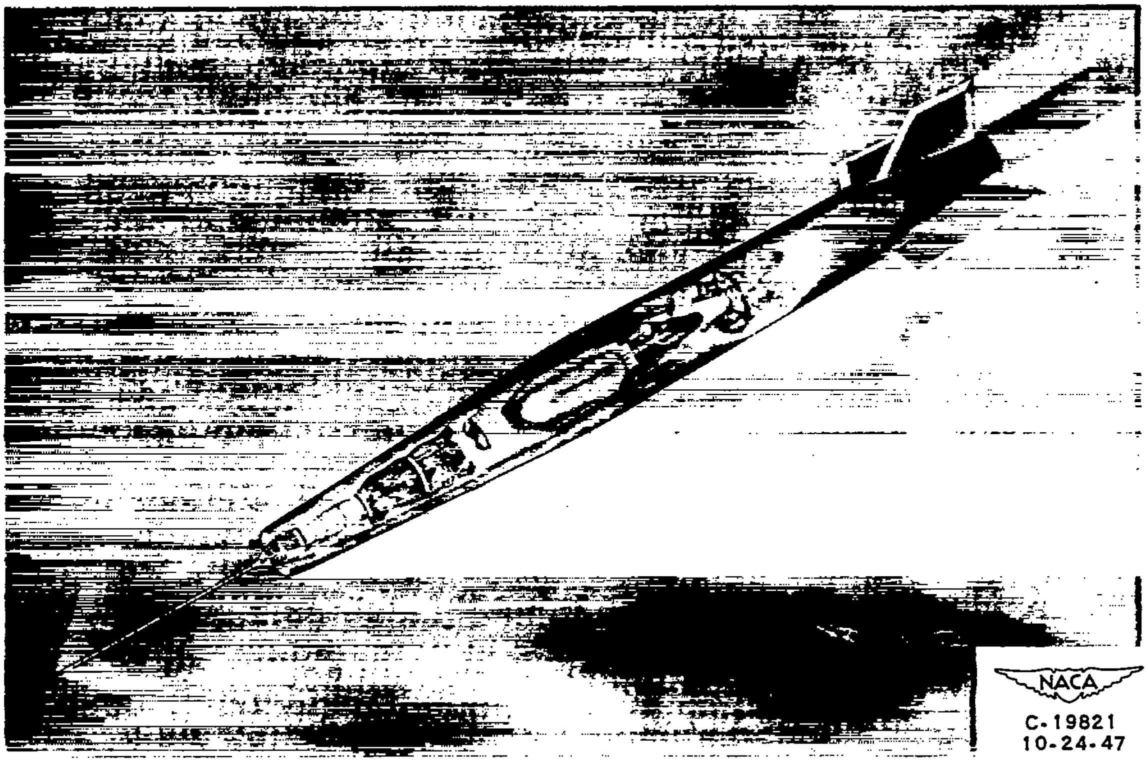


Figure 2. - Cutaway view of 16-inch ram-jet unit during free flight.

[redacted]

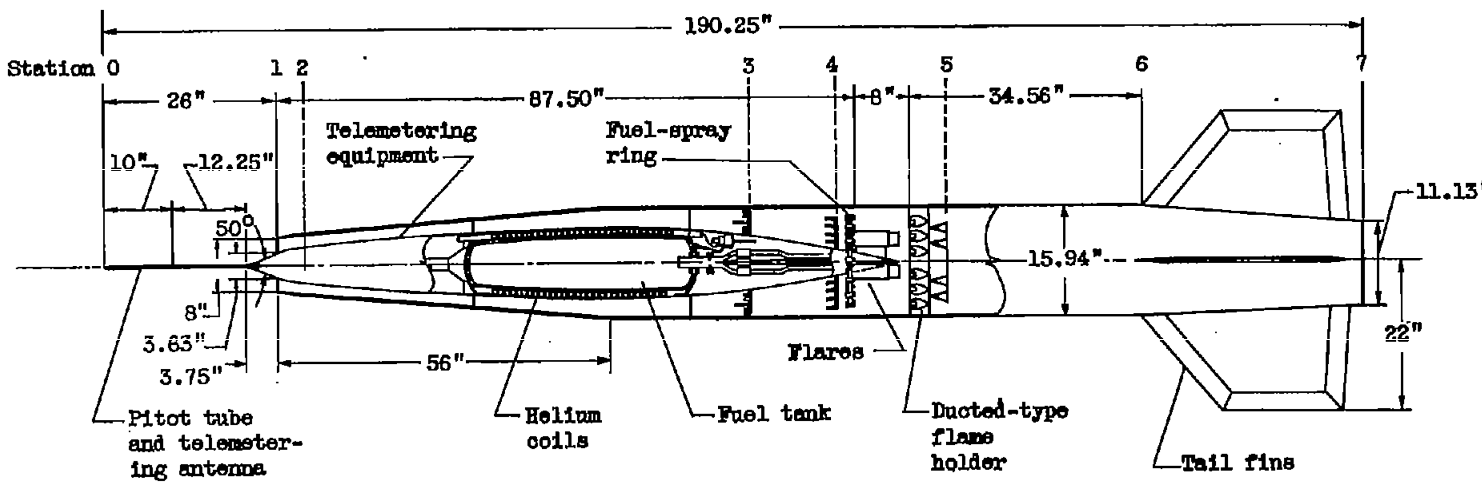


Figure 3. - Schematic cross-sectional diagram of supersonic 16-inch ram-jet unit. (Dimensions given for model A.)

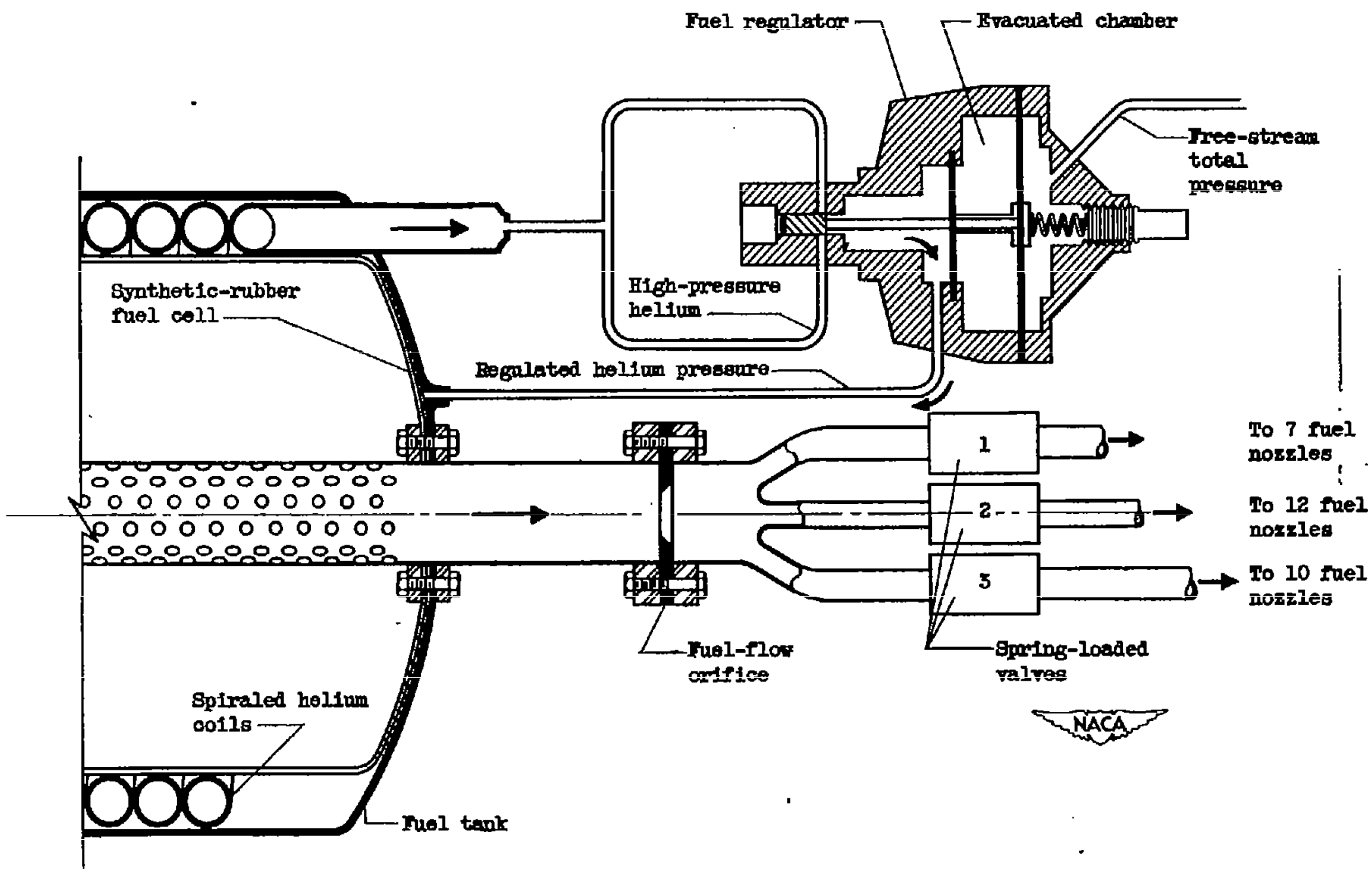


Figure 4. - Schematic diagram of fuel system for supersonic 16-inch ram-jet unit.

1152

(a) Three-quarter front view.

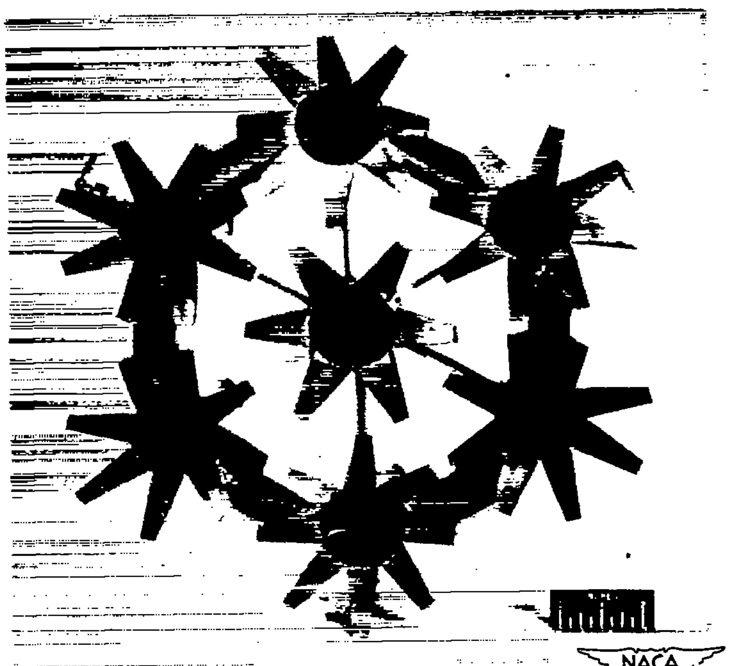
(b) Three-quarter rear view.
Figure 5. - Flame holder for supersonic ram-jet units 16-A-2, 16-A-3, and 16-A-4.

[redacted]

1152

C-21694
6-9-48

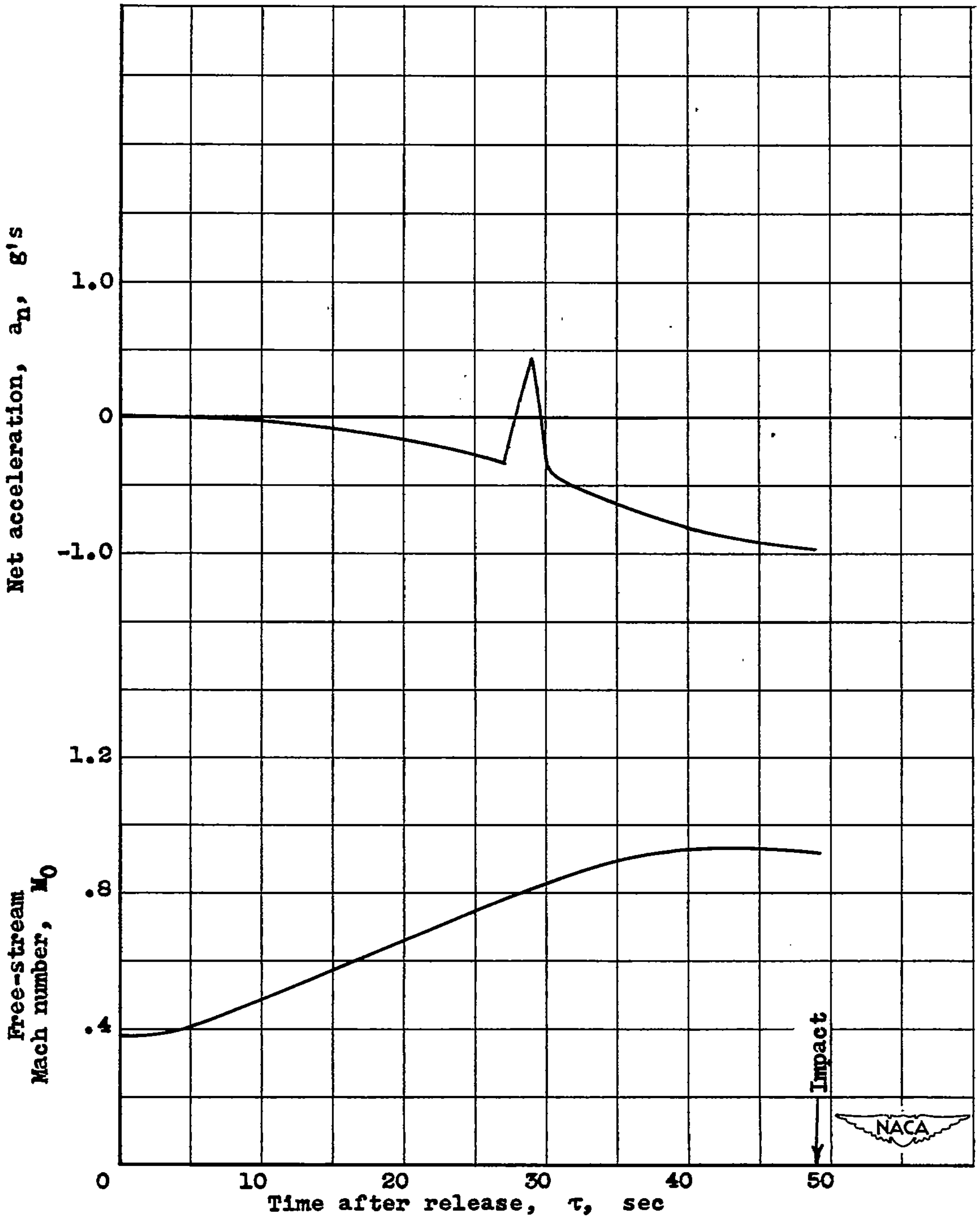
(a) Three-quarter rear view.



C-21695
6-9-48

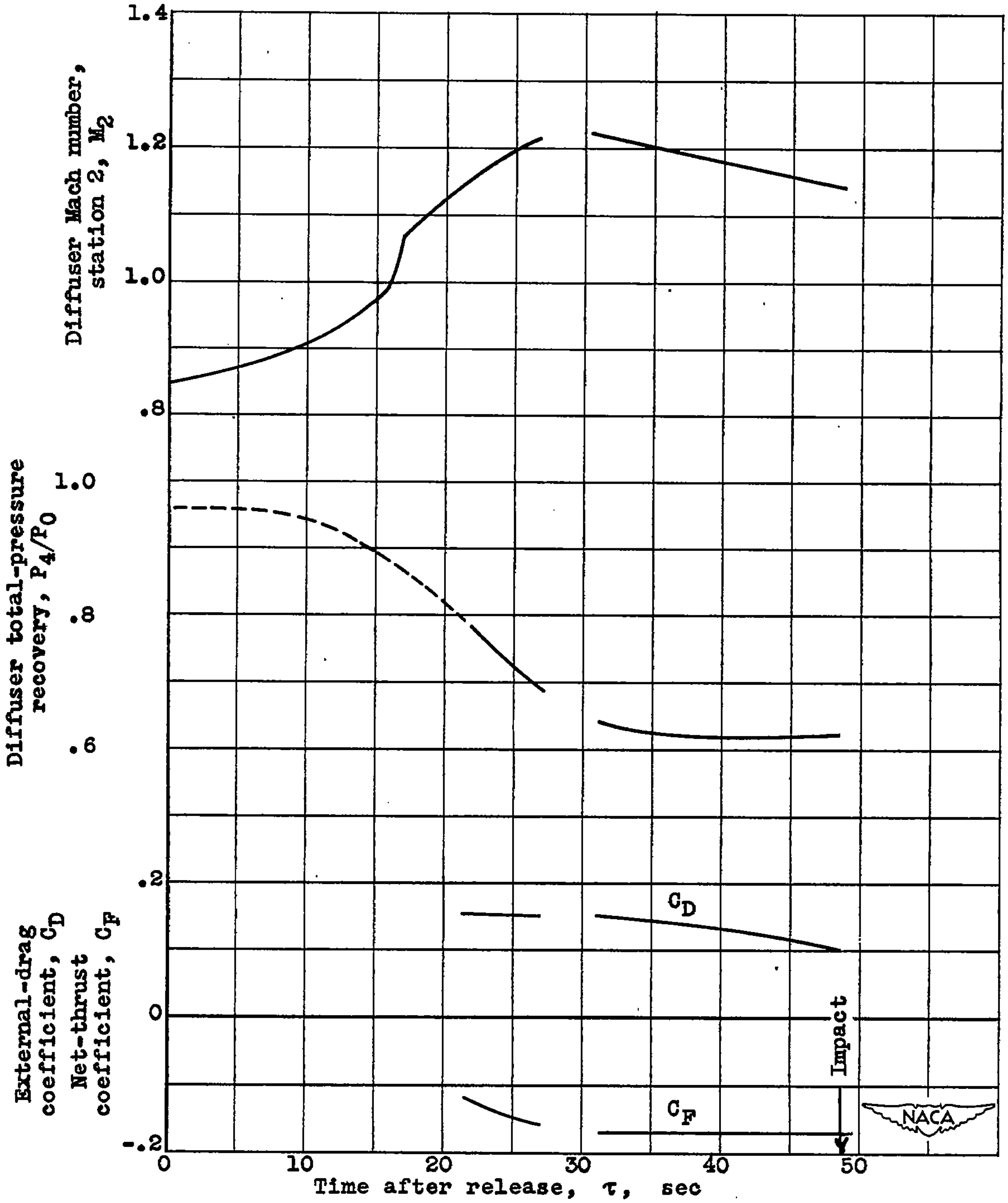
(b) Rear view.

Figure 6. - Flame holder for supersonic ram-jet unit 16-A-5.



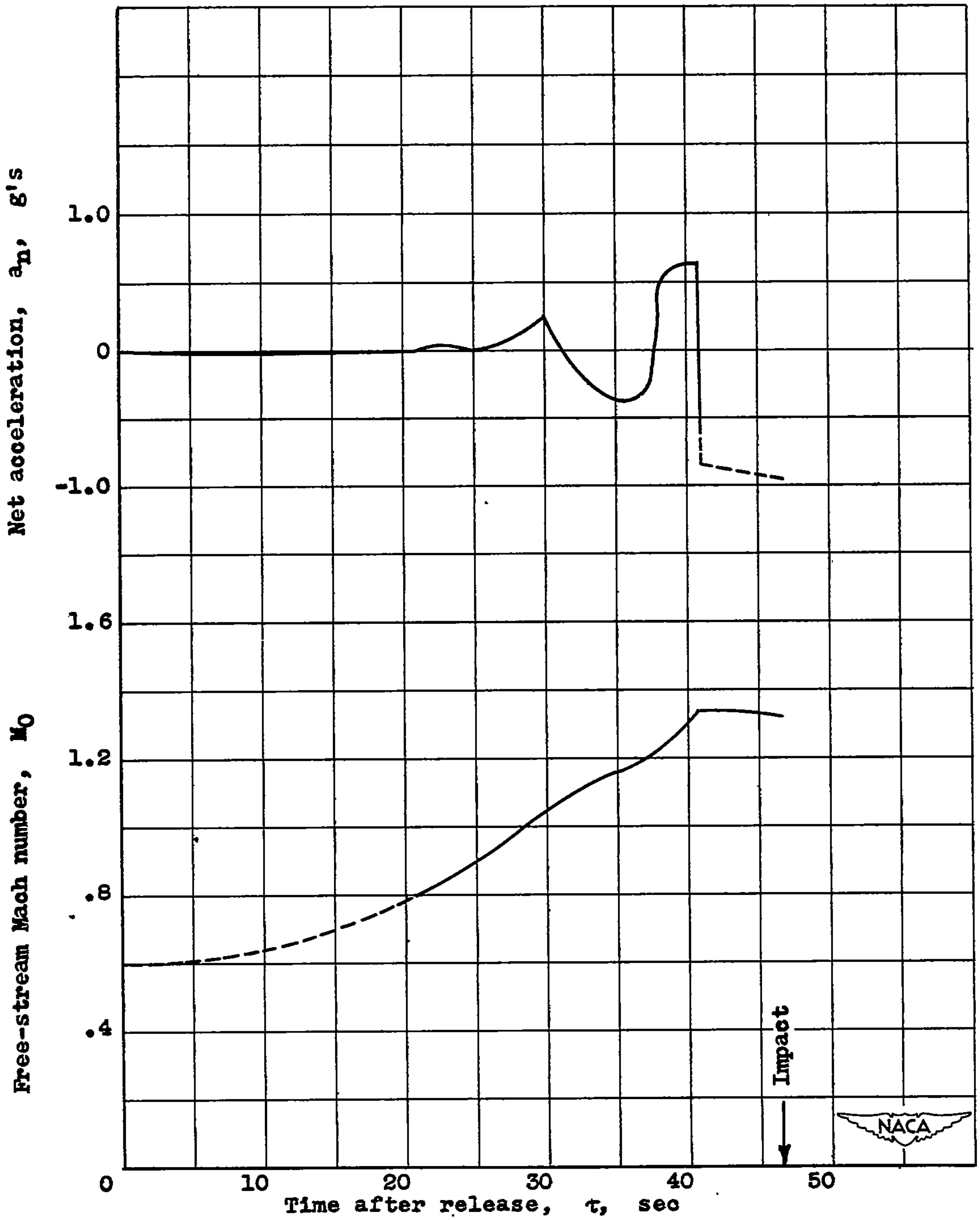
(a) Resultant flight conditions.

Figure 7. - Time history of flight data and performance of ram-jet unit 16-A-2.



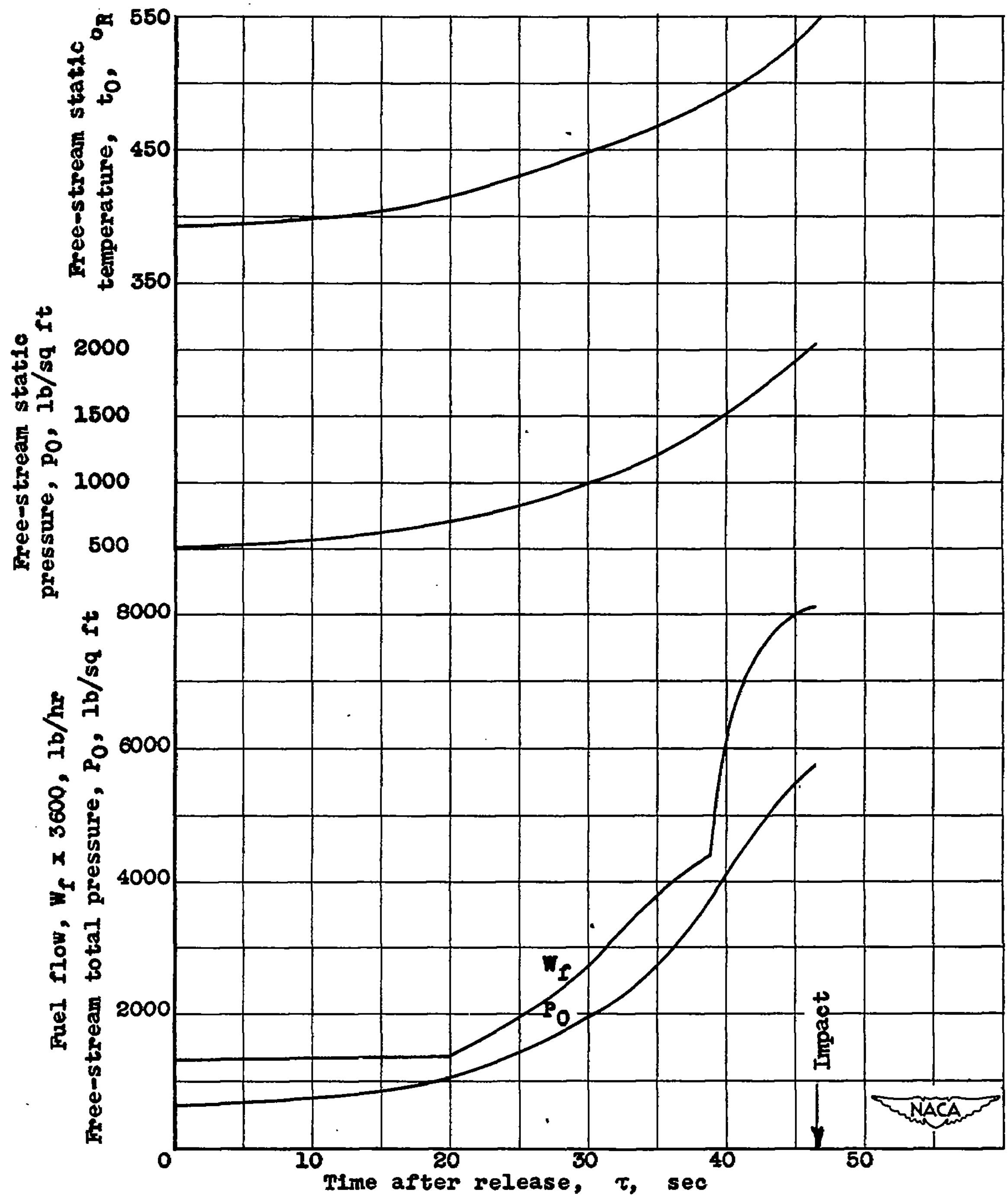
(b) Diffuser conditions and external-drag and net-thrust coefficients.

Figure 7. - Concluded. Time history of flight data and performance of ram-jet unit 16-A-2.



(a) Resultant flight conditions.

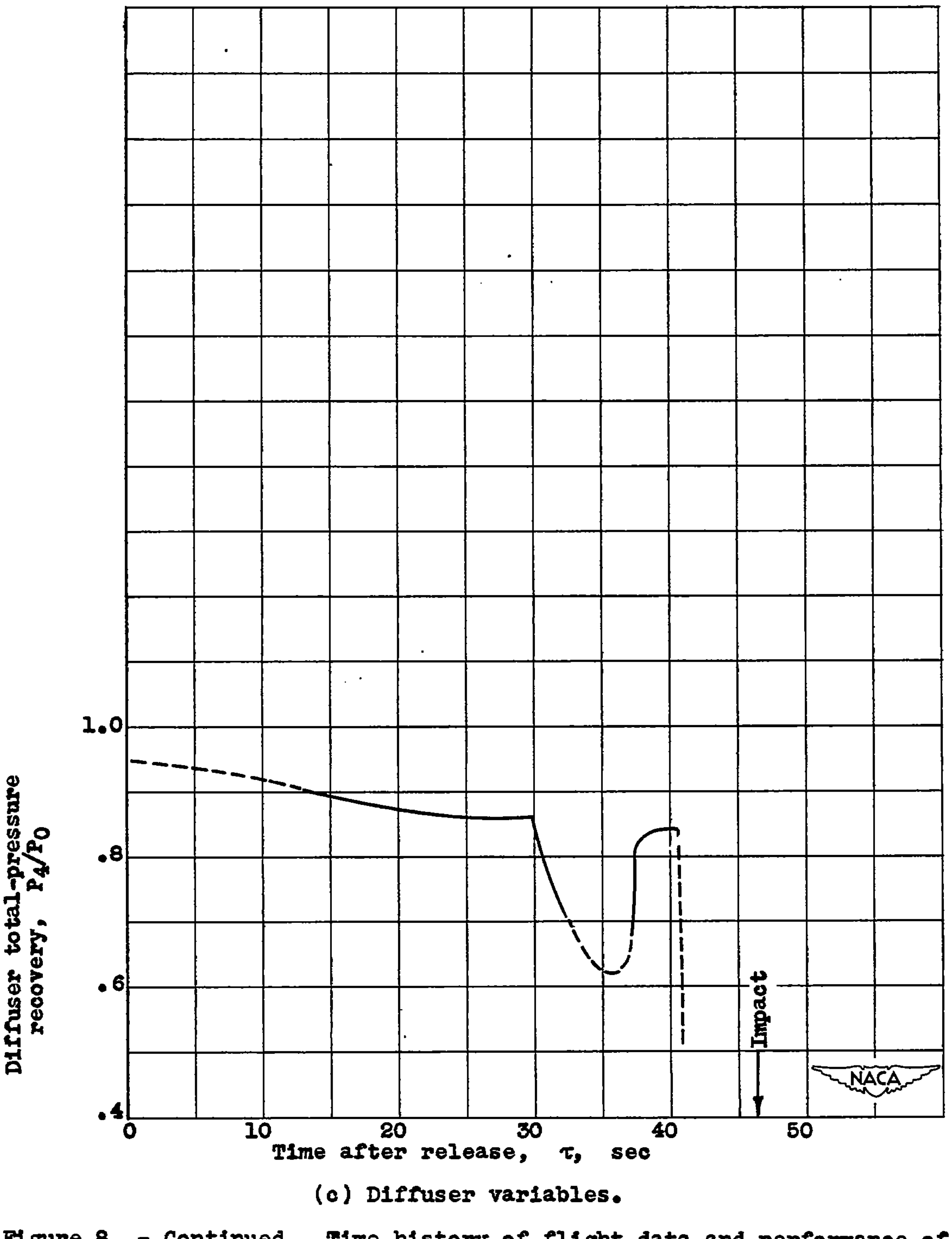
Figure 8. - Time history of flight data and performance of ram-jet unit 16-A-3.



(b) Independent test variables.

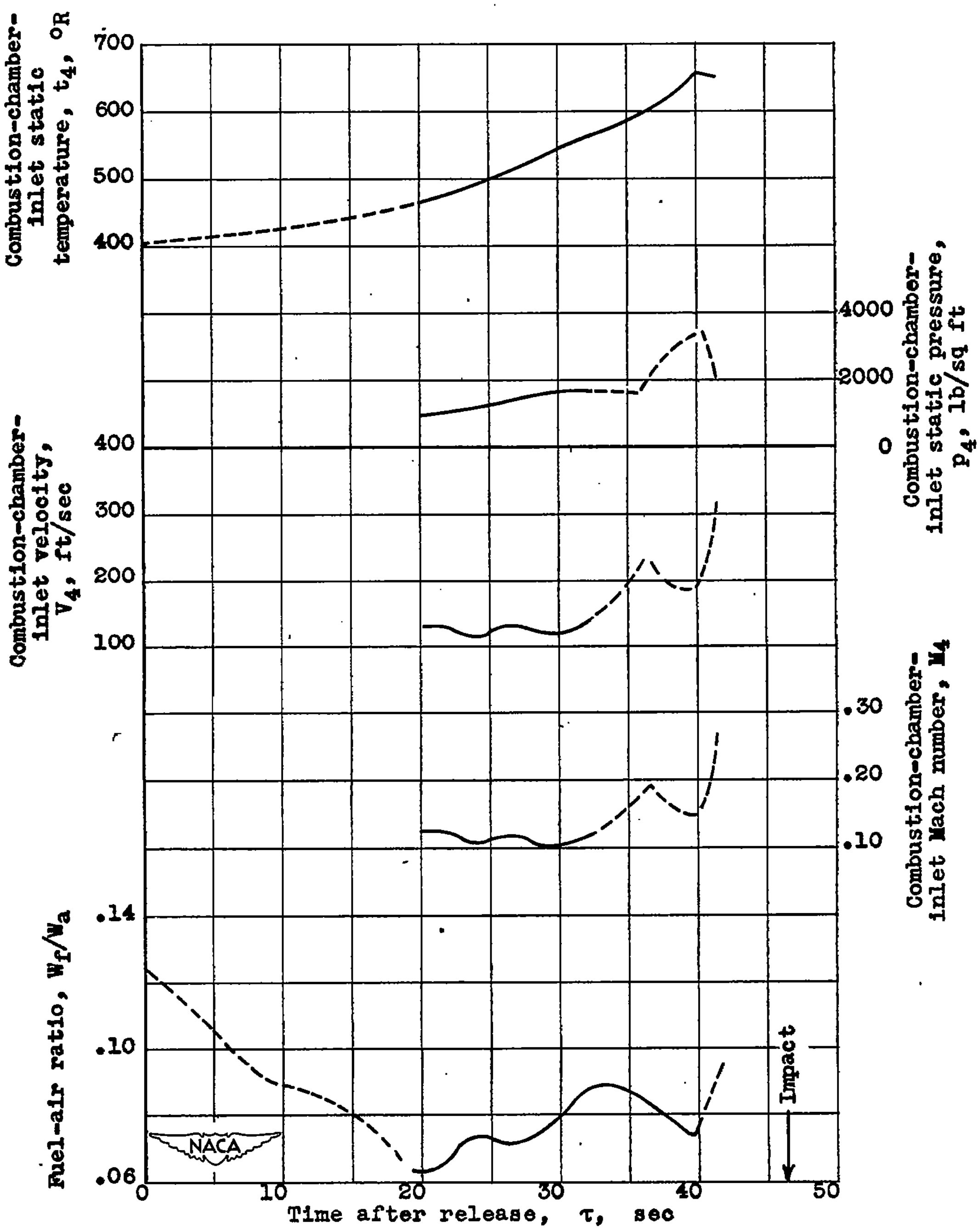
Figure 8. - Continued. Time history of flight data and performance of ram-jet 16-A-3.

1152



(c) Diffuser variables.

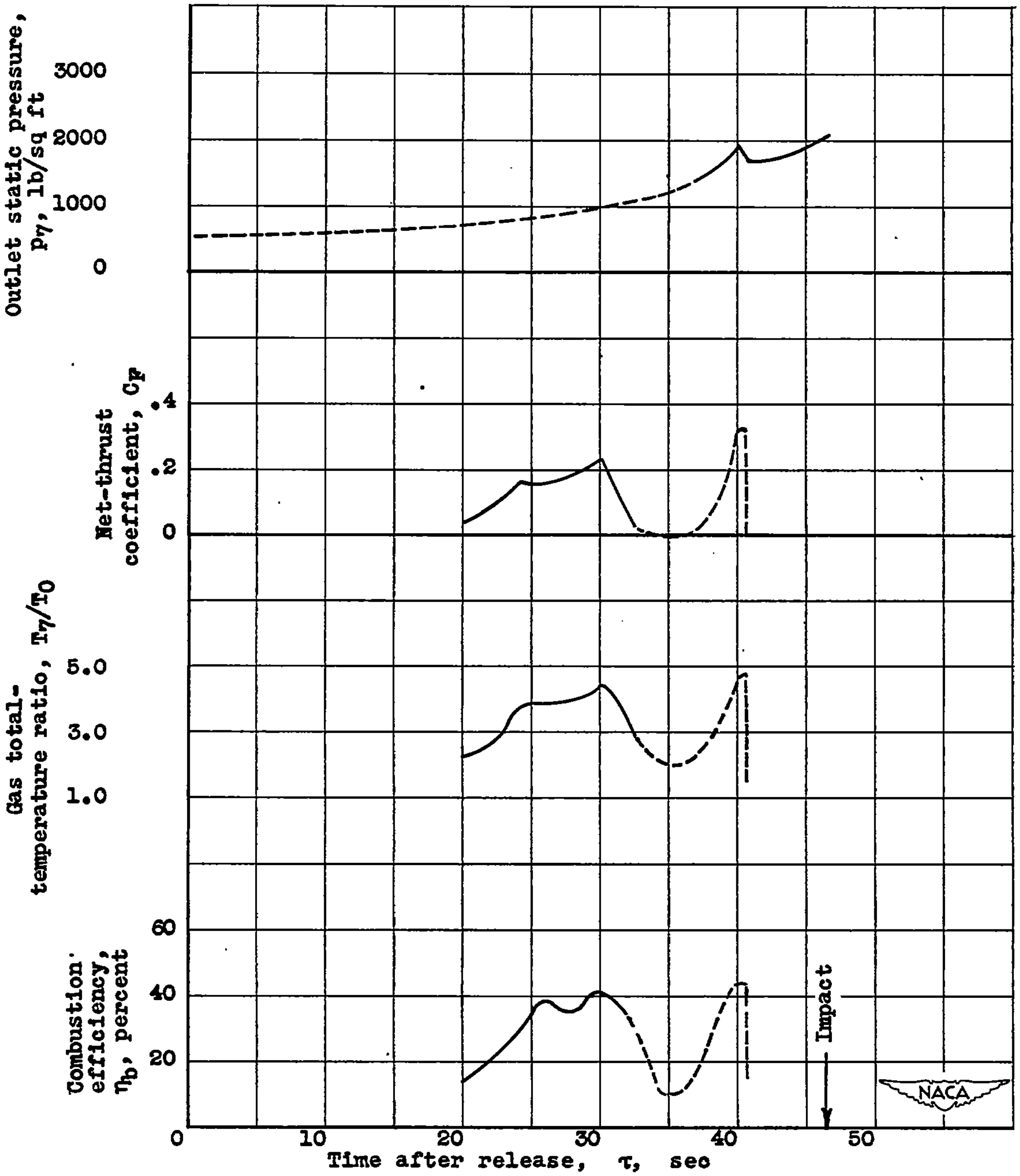
Figure 8. - Continued. Time history of flight data and performance of ram-jet 16-A-3.



(d) Combustion-chamber-inlet variables.

Figure 8. - Continued. Time history of flight data and performance of ram-jet unit 16-A-3.

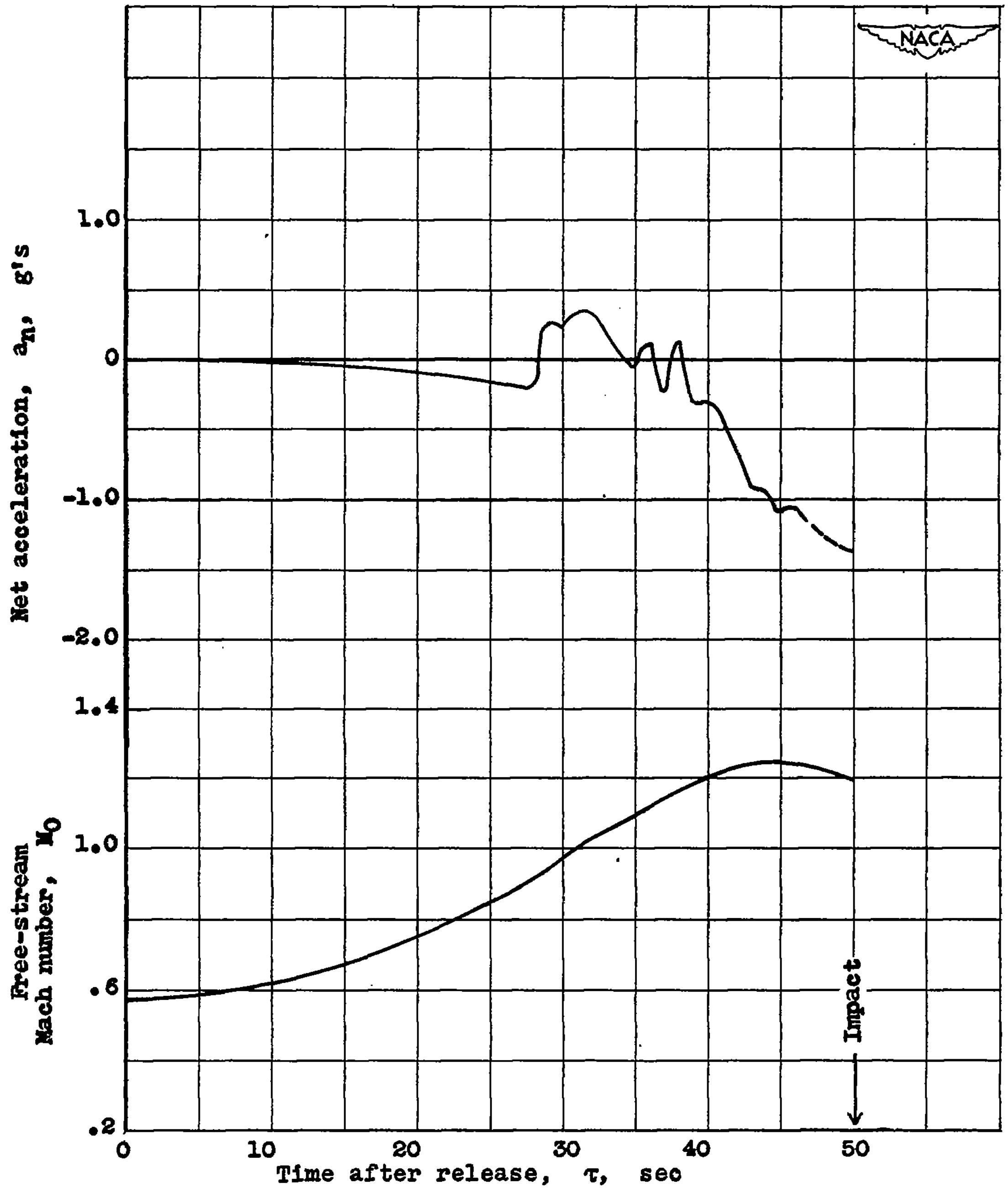
1152



(e) Performance variables.

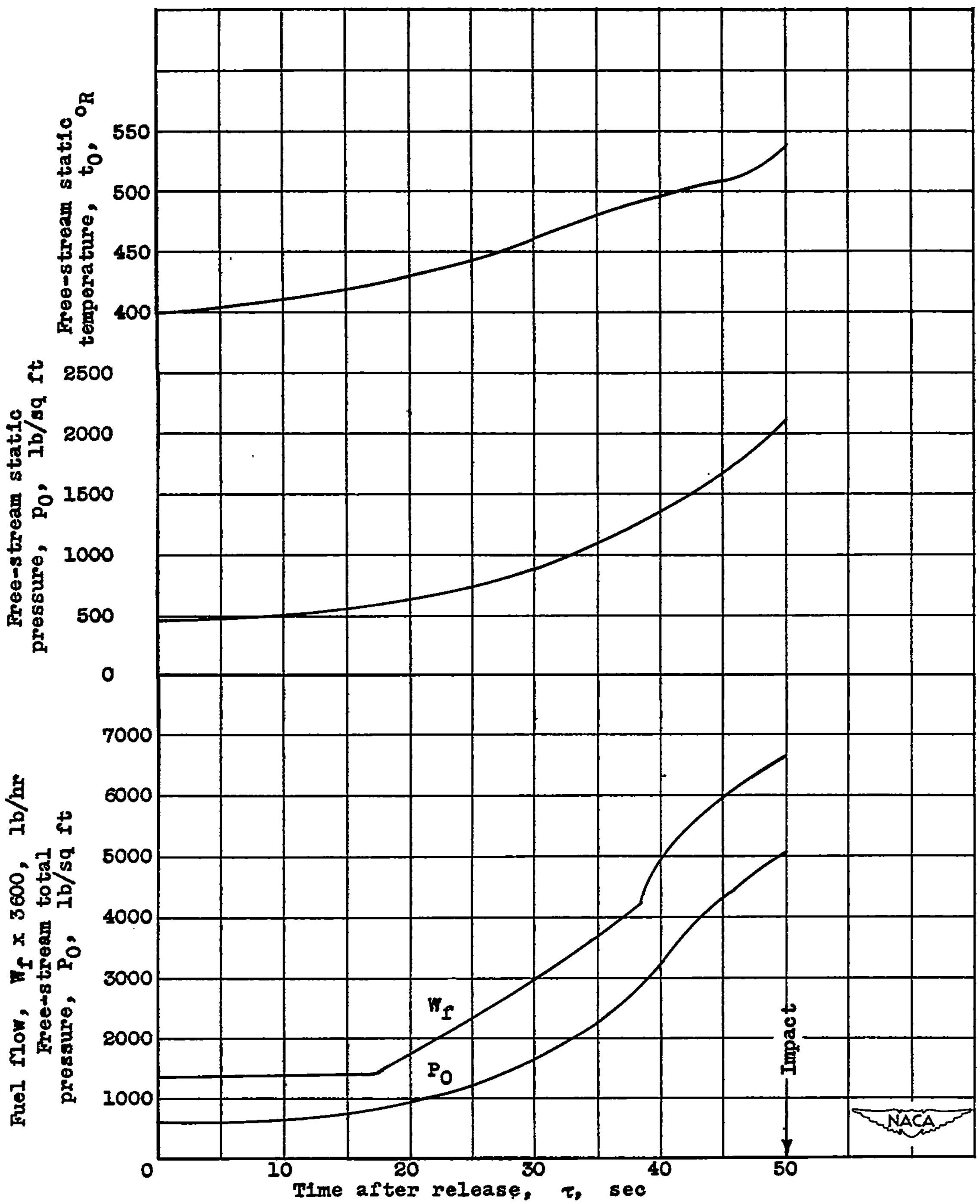
Figure 8. - Concluded. Time history of flight data and performance of ram-jet unit 16-A-3.

1152



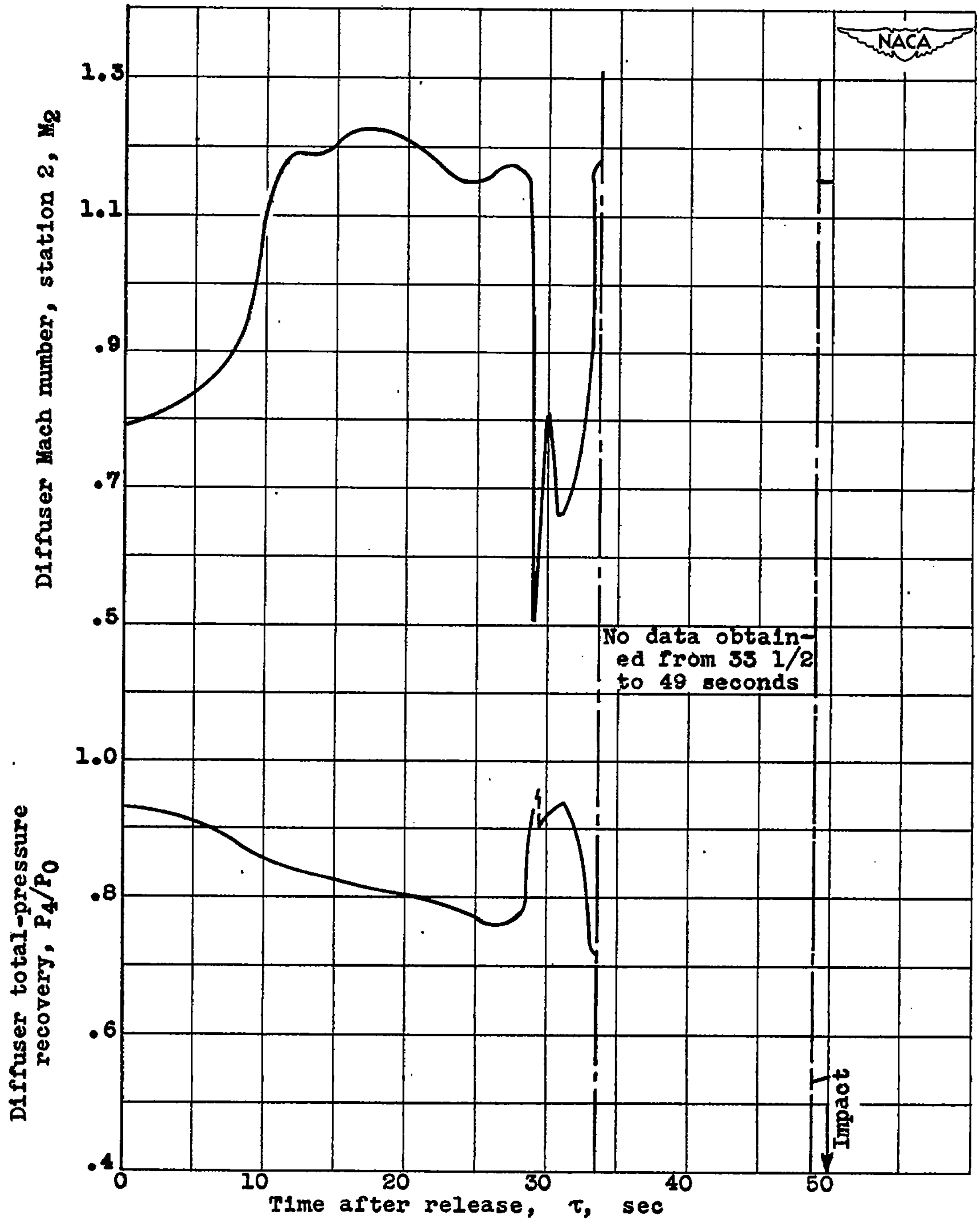
(a) Resultant flight conditions.

Figure 9. - Time history of flight data and performance of ram-jet unit 16-A-4.



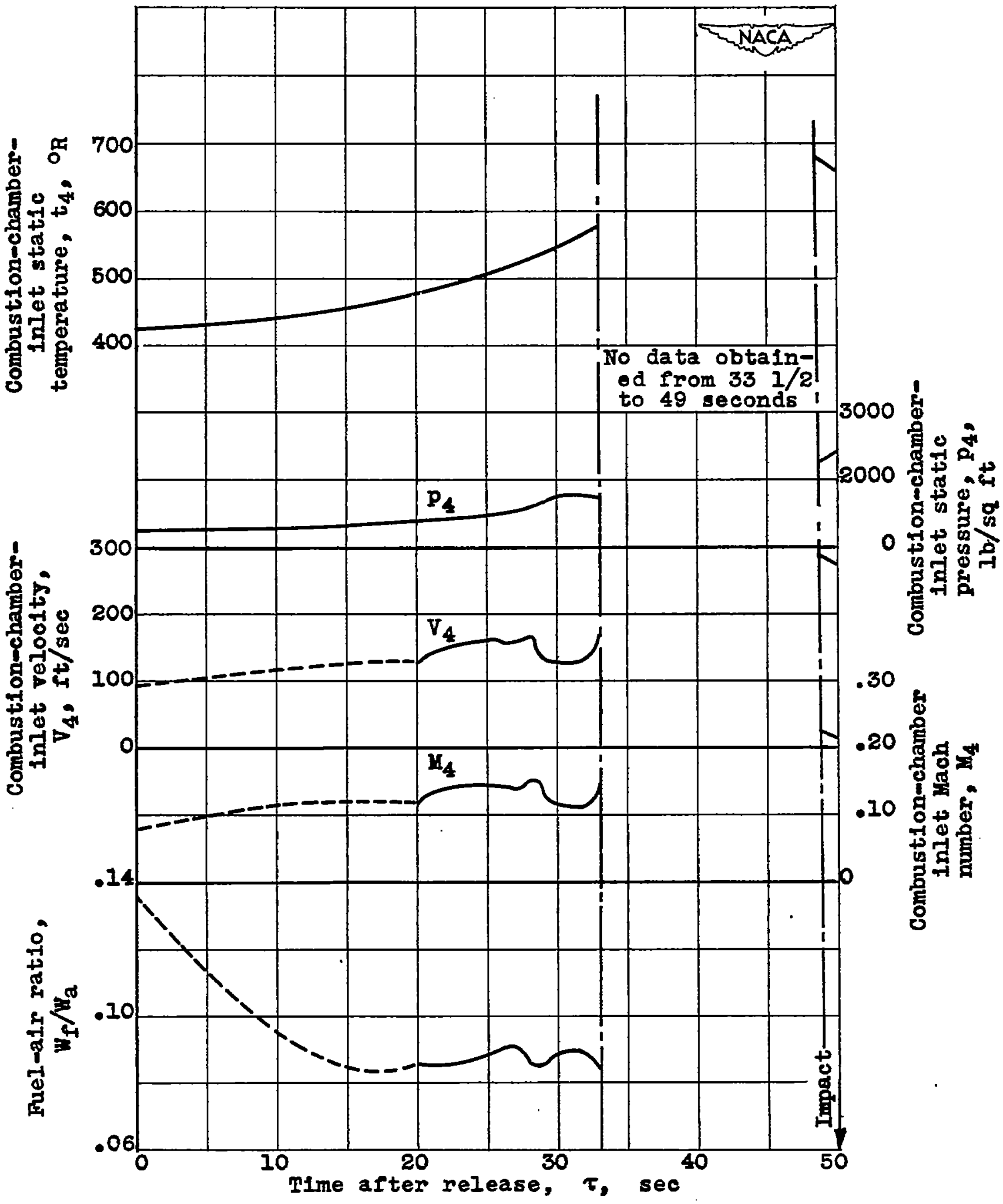
(b) Independent test variables.

Figure 9. - Continued. Time history of flight data and performance of ram-jet unit 16-A-4.



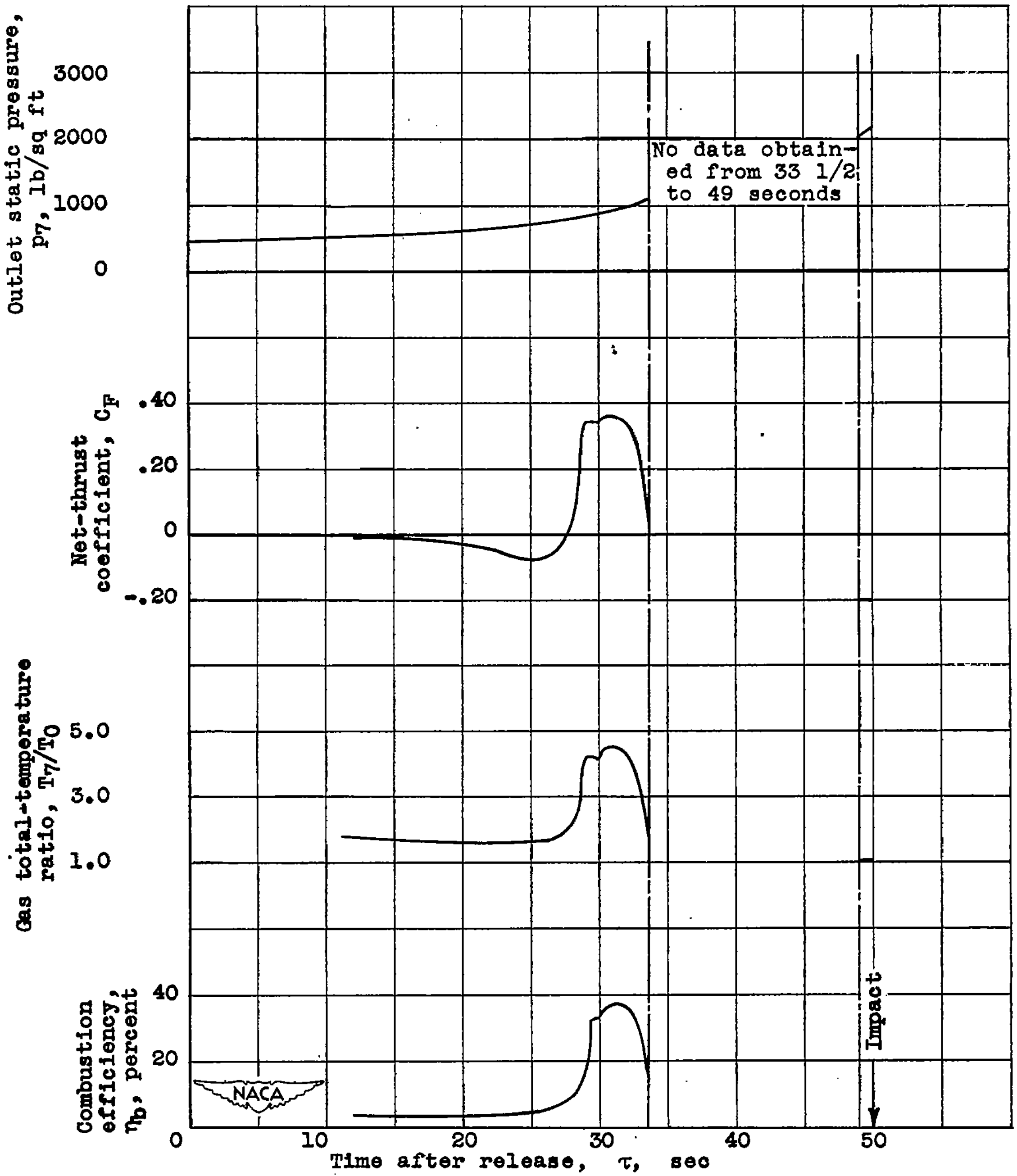
(c) Diffuser variables.

Figure 9. - Continued. Time history of flight data and performance of ram-jet unit 16-A-4.



(d) Combustion-chamber-inlet variables.

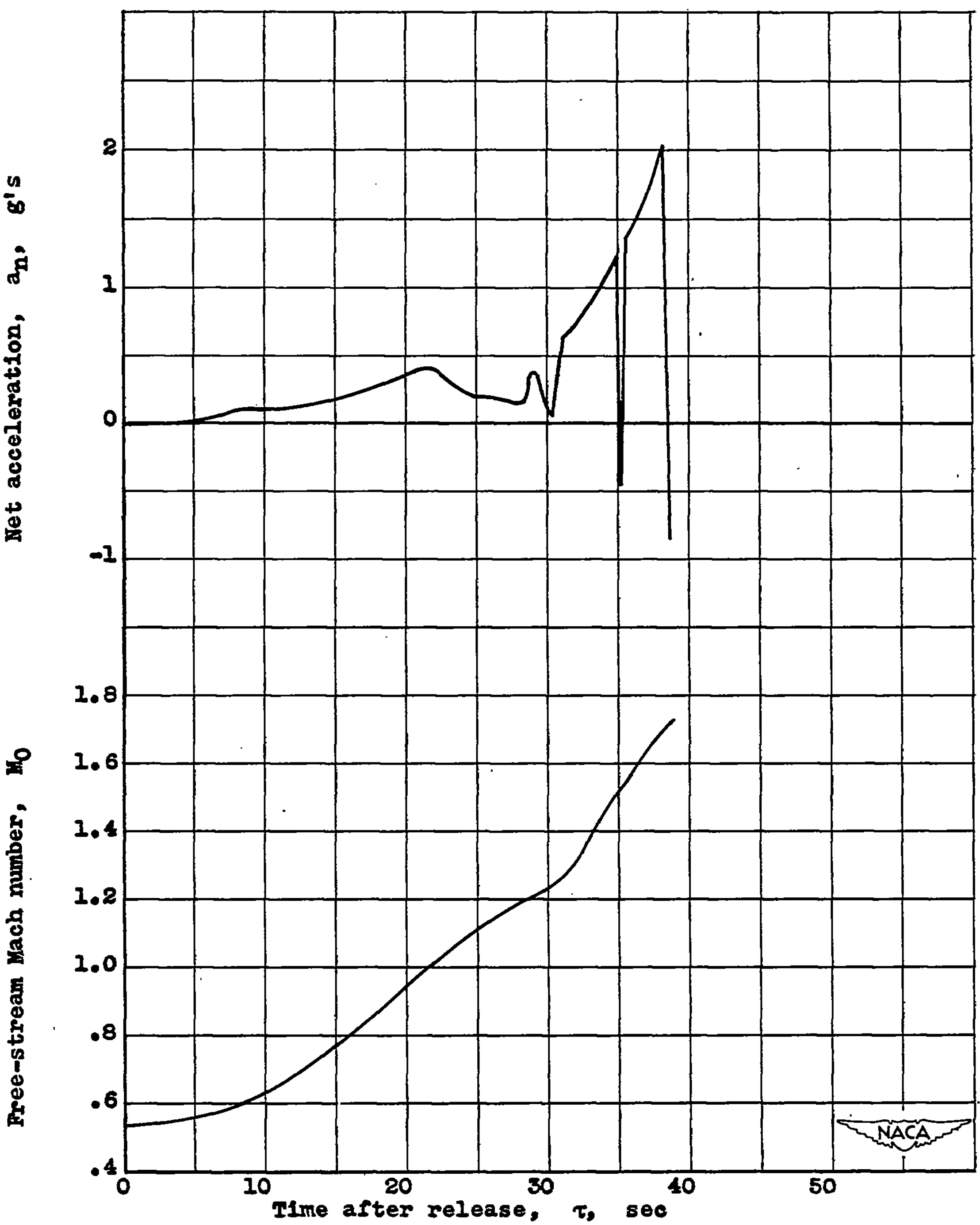
Figure 9. - Continued. Time history of flight data and performance of ram-jet unit 16-A-4.



(e) Performance variables.

Figure 9. - Concluded. Time history of flight data and performance of ram-jet unit 16-A-4.

1152

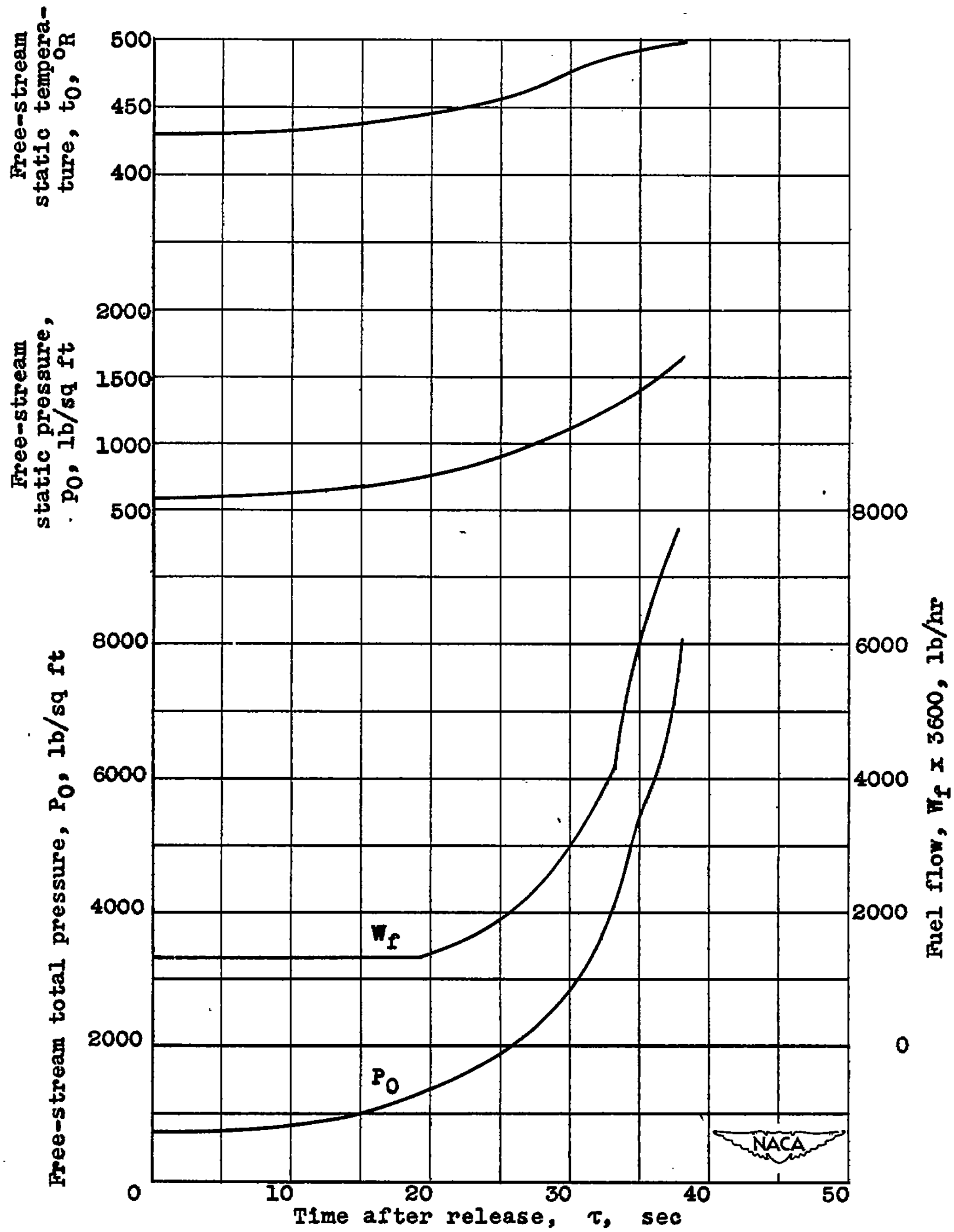


(a) Resultant flight conditions.

Figure 10. - Time history of flight data and performance of ram-jet unit 16-A-5.

[redacted]

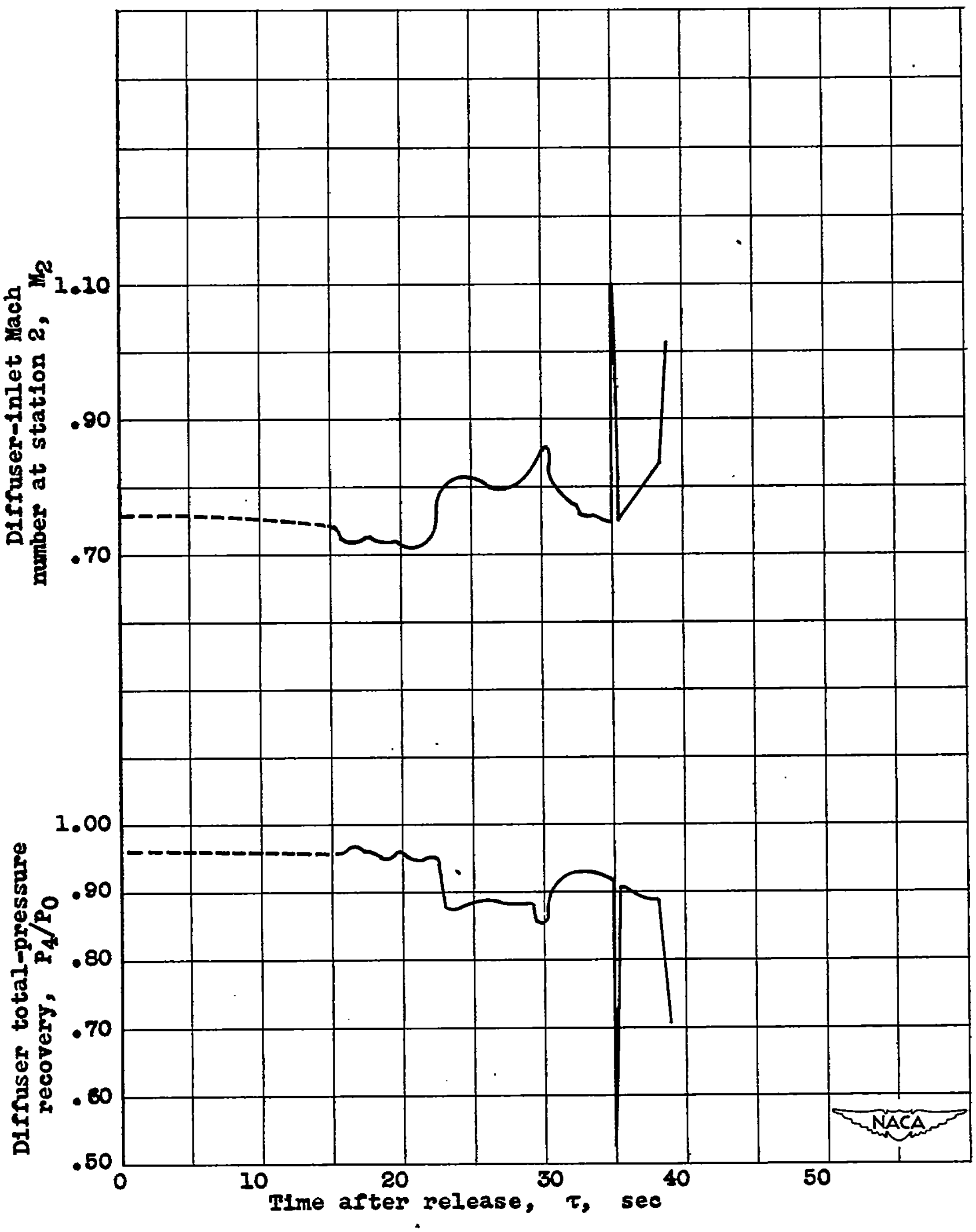
1152



(b) Independent test variables.

Figure 10. - Continued. Time history of flight data and performance of ram-jet unit 16-A-5.

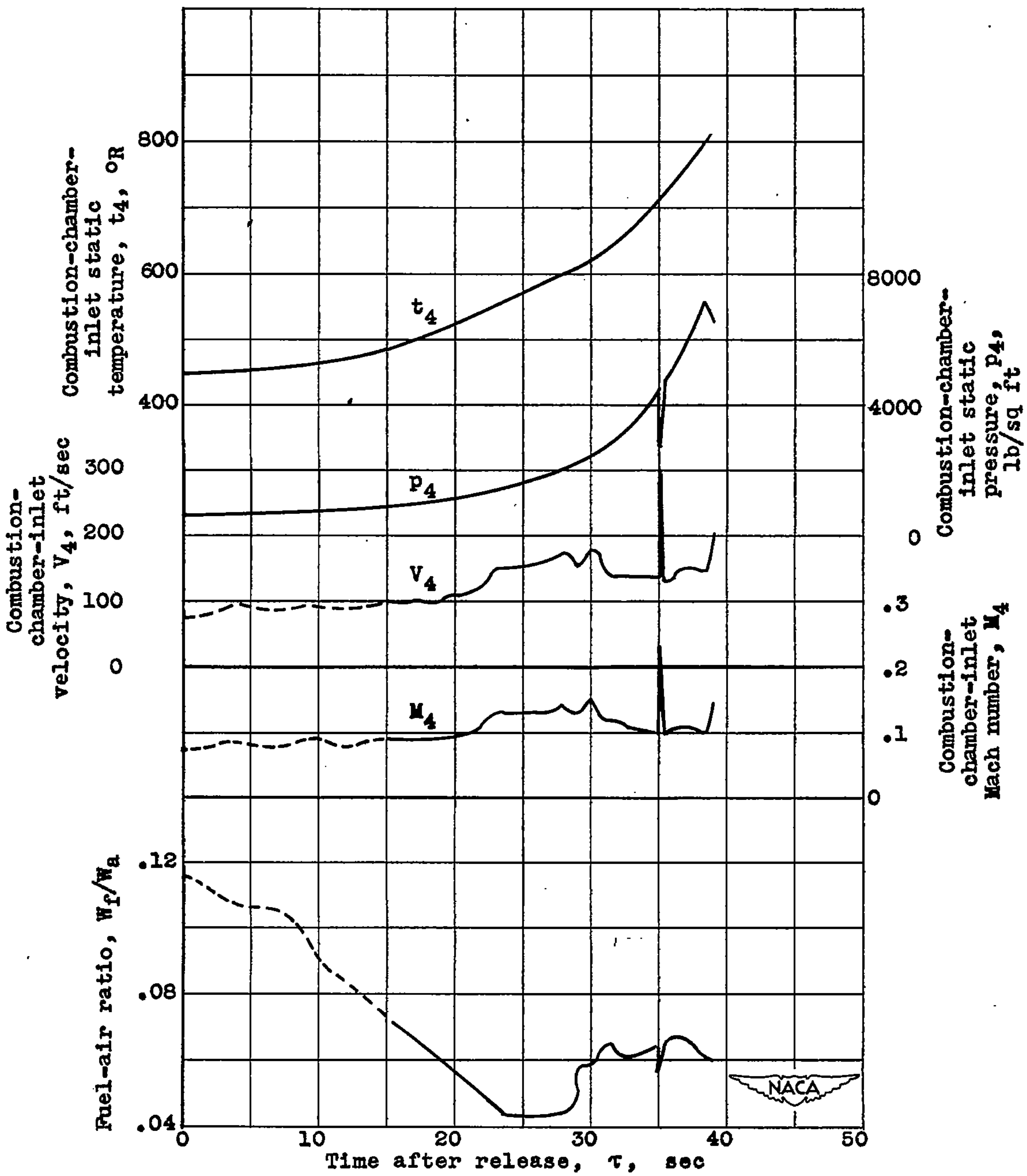
1152



(c) Diffuser variables.

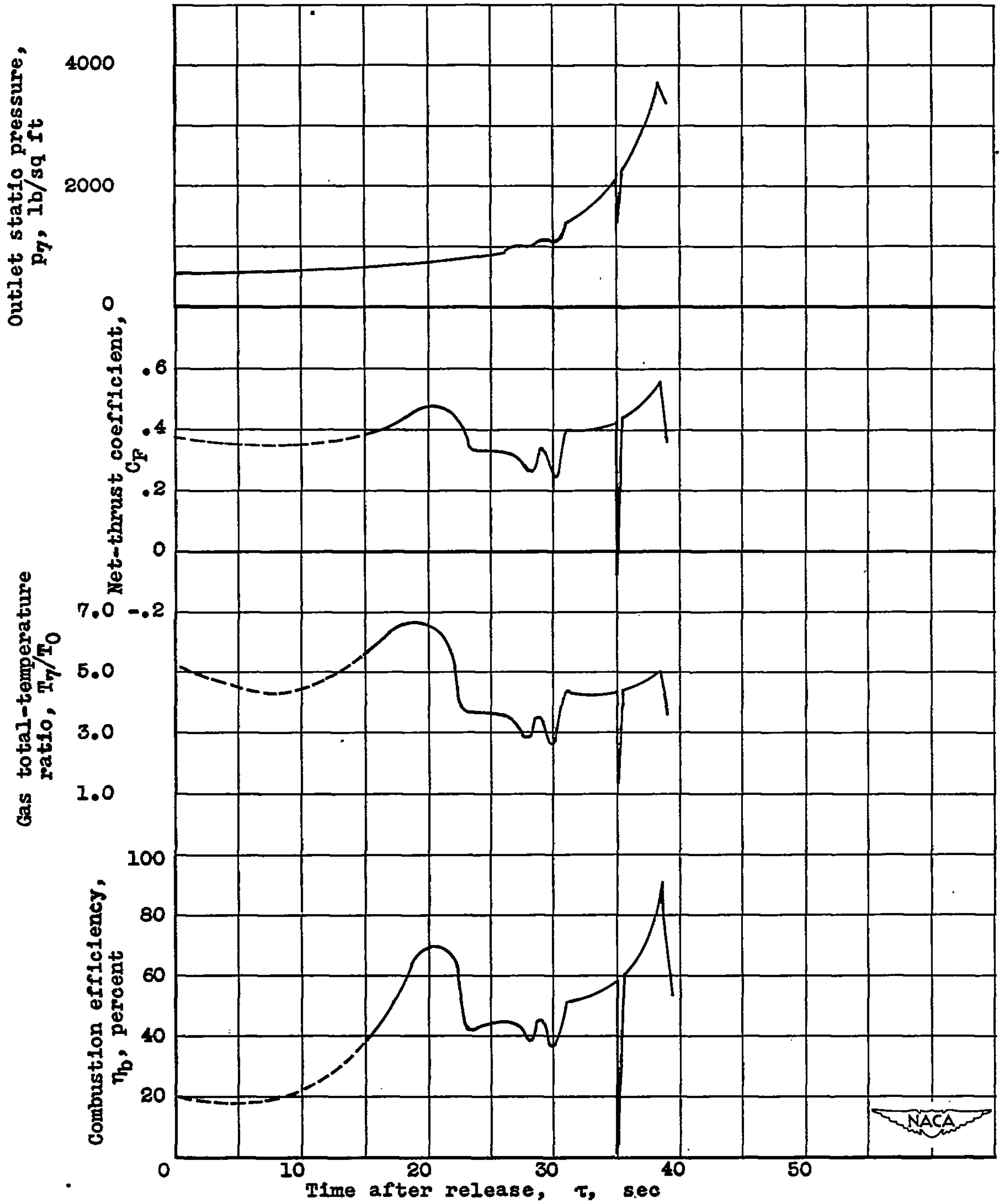
Figure 10. - Continued. Time history of flight data and performance of ram-jet unit 16-A-5.

1152



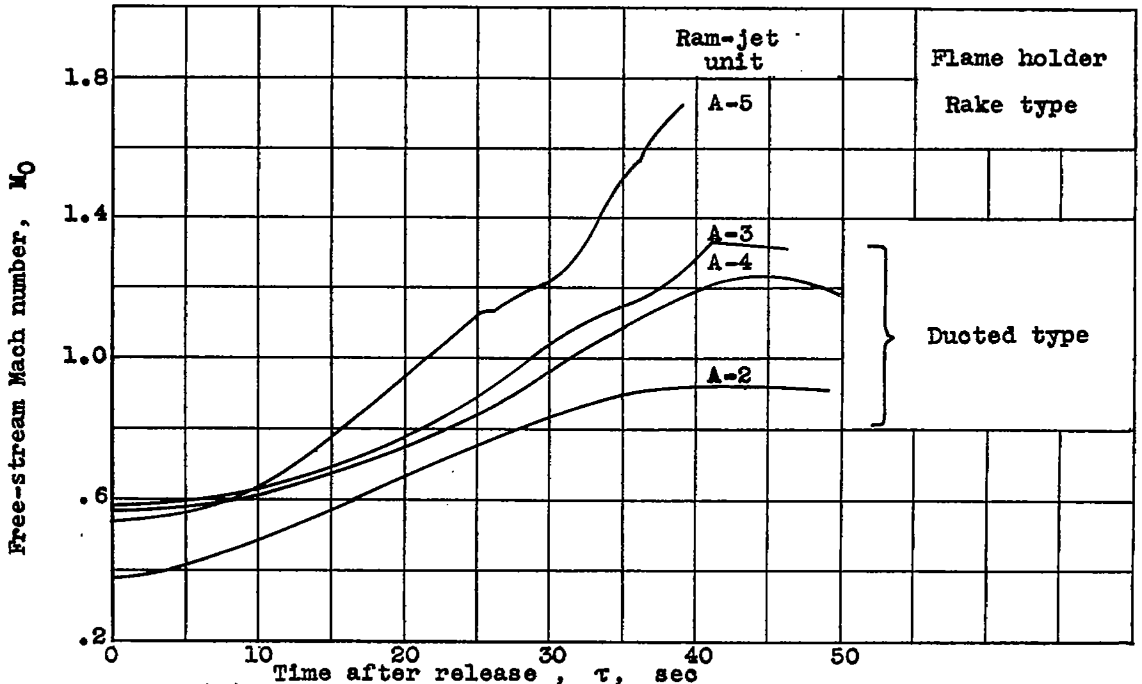
(d) Combustion-chamber-inlet variables.

Figure 10. - Continued. Time history of flight data and performance of ram-jet unit 16-A-5.

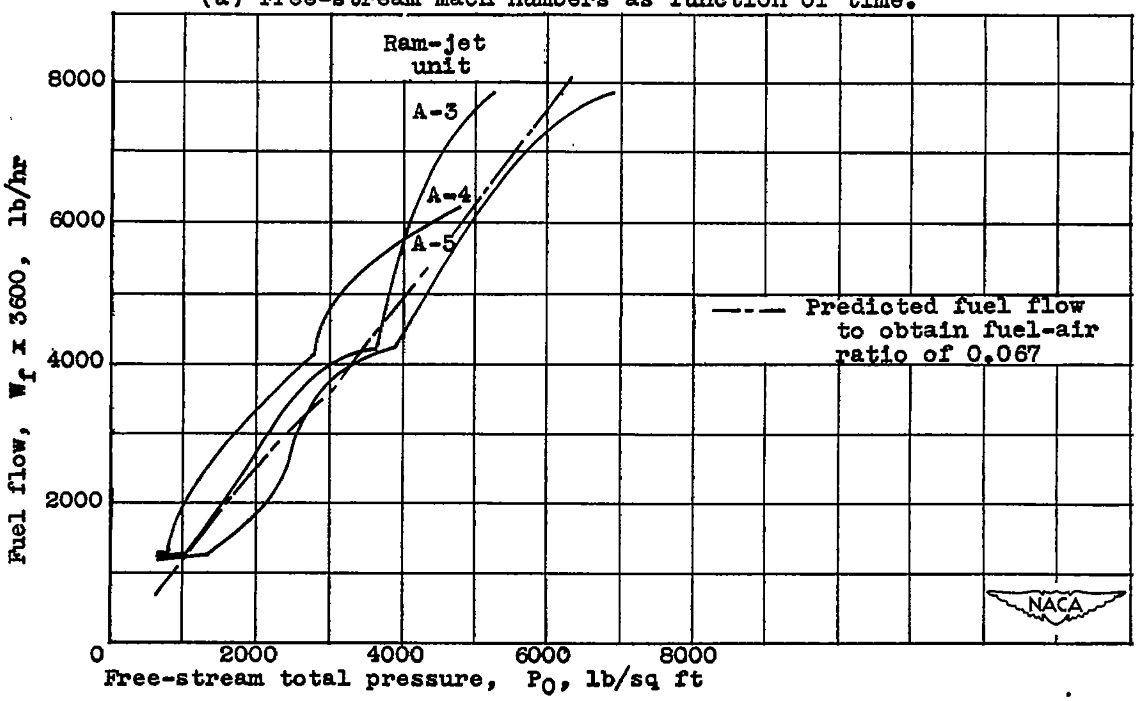


(e) Performance variables.

Figure 10. - Concluded. Time history of flight data and performance of ram-jet unit 16-A-5.



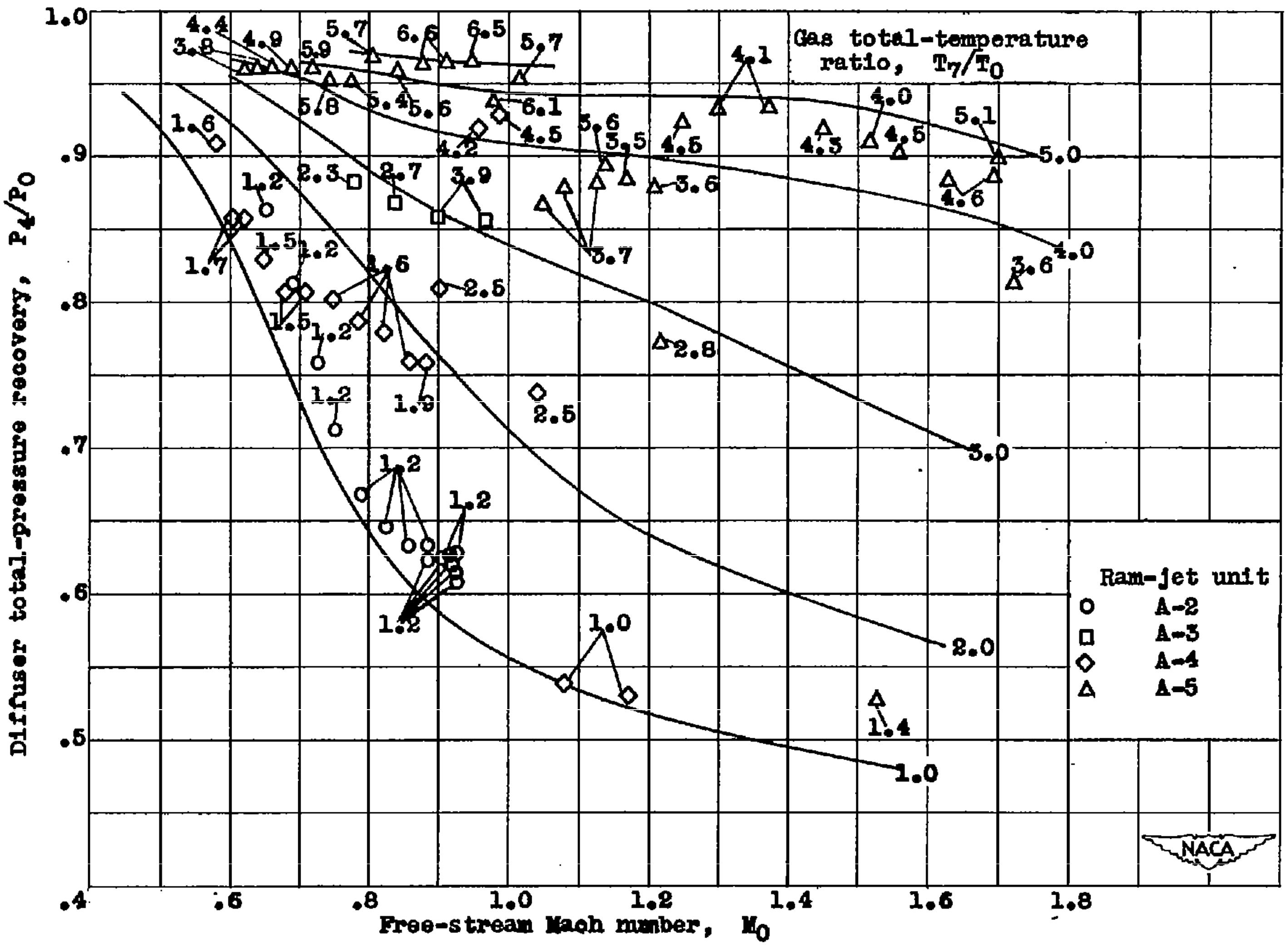
(a) Free-stream Mach numbers as function of time.



(b) Fuel flow as function of free-stream total pressure.

Figure 11. - Comparison of free-stream Mach numbers and fuel flows for ram-jet units 16-A-2, 16-A-3, 16-A-4, and 16-A-5.

[redacted]



[redacted]

Figure 12. - Diffuser total-pressure recovery as function of free-stream Mach number at various gas total-temperature ratios for ram-jet units 16-A-2, 16-A-3, 16-A-4, and 16-A-5.

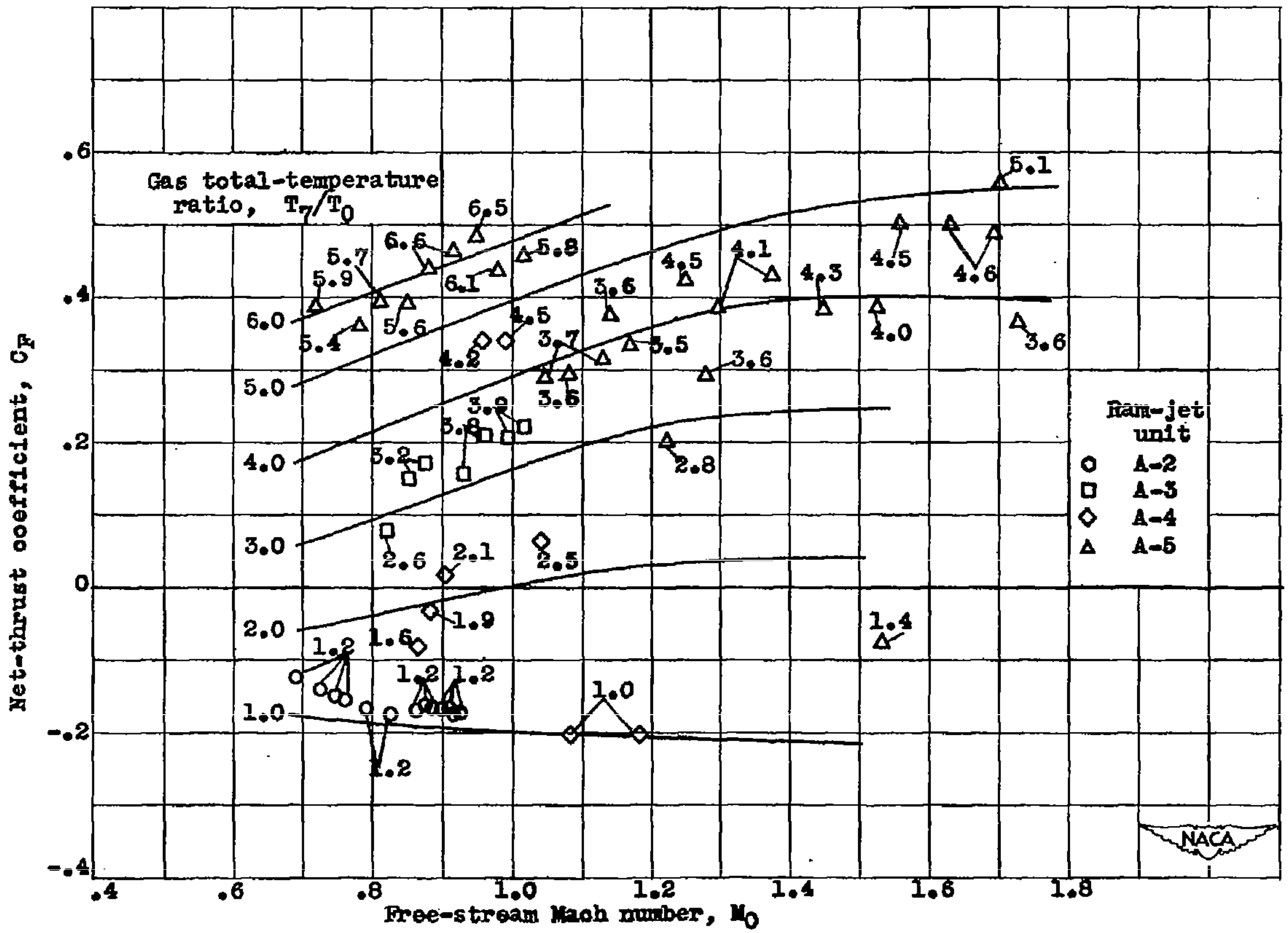


Figure 13. - Net-thrust coefficient as function of free-stream Mach number at various gas total-temperature ratios for ram-jet units 16-A-2, 16-A-3, 16-A-4, and 16-A-5.

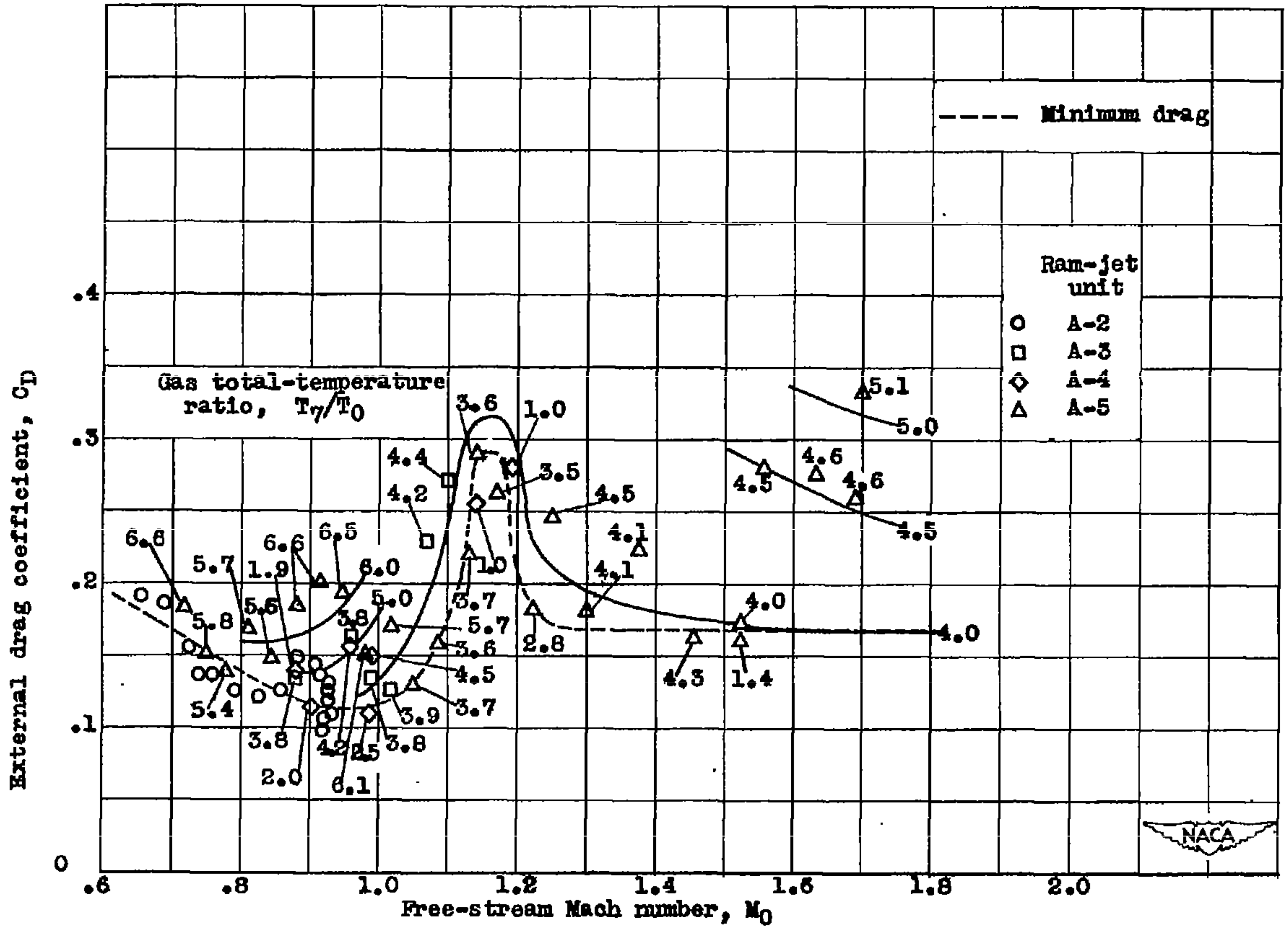


Figure 14. - External drag coefficient as function of free-stream Mach number at various gas total-temperature ratios for ram-jet units 16-A-2, 16-A-3, 16-A-4, and 16-A-5. (All circular data points have gas total-temperature value of 1.2.)